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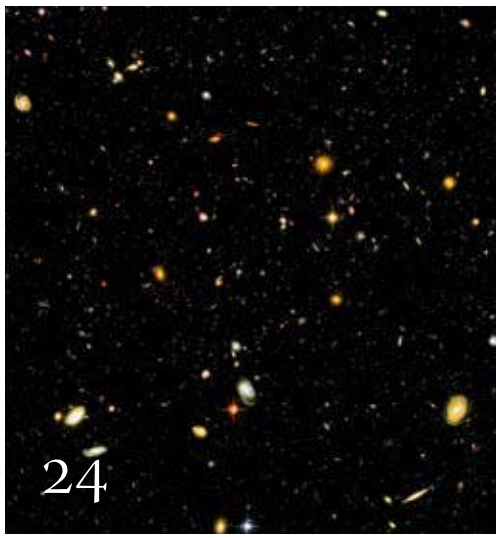

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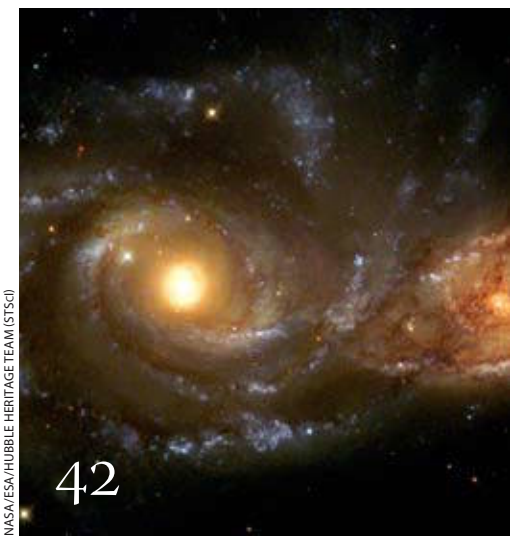

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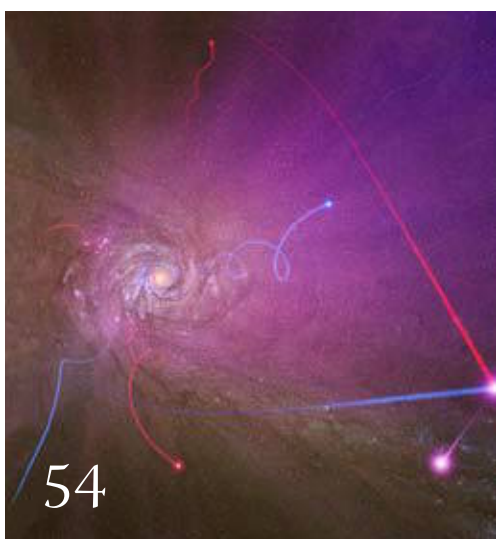

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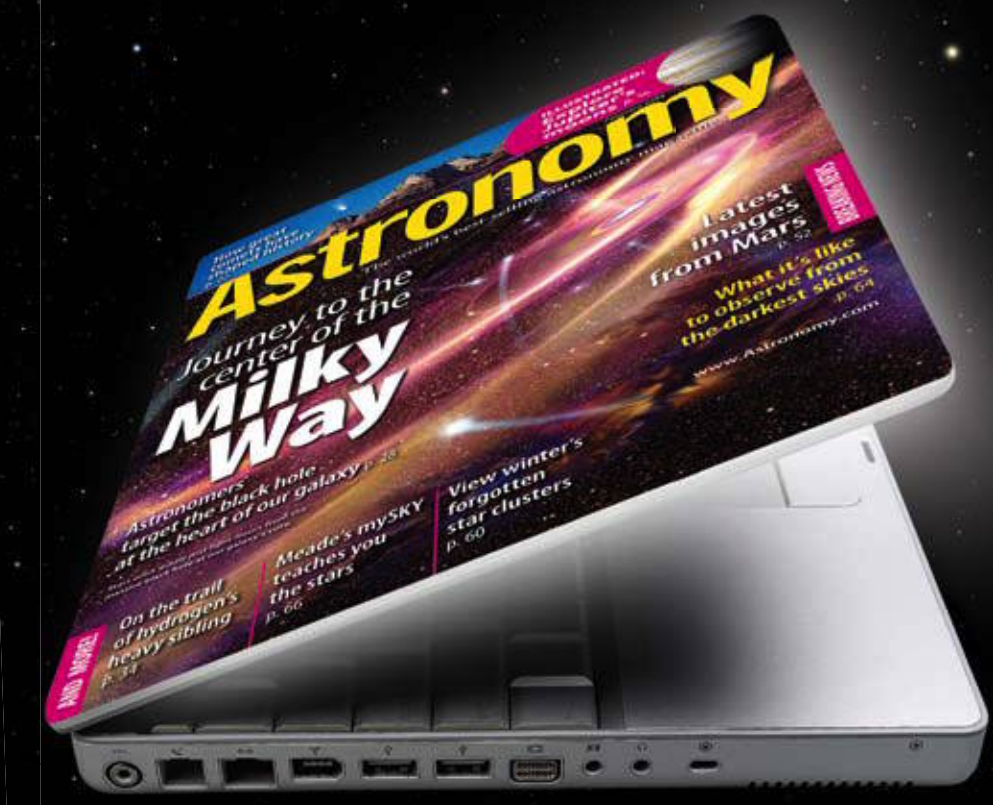
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The meaning of it all

Cosmology cuts straight to the heart of why many of us love astronomy. It's the study of how the universe evolves, and it attacks the "big questions" we all would like answered. How did the Big Bang happen? What will be the fate of the cosmos? What processes govern the way stars, galaxies, and black holes behave?

In this special edition magazine from the editors of *Astronomy*, you'll get a state-of-the-art view of the research astronomers are conducting on those scientific issues. Moreover, the stories presented here are written by a who's who of the greatest cosmologists and science writers in the business. Thirteen feature stories cover the spectrum of cosmology, from an overview of the universe's first billion years to a compendium of five important things you simply have to know about cosmology.

I'd like to point you in the direction of several stories that lie at the heart of cosmology's big questions. In "How the Big Bang forged the first elements" (p. 18), University of Rochester astrophysicist Adam Frank tells the story of the first crucial stage of the universe that made matter — including stars, galaxies, planets, and people — possible. Caltech's Richard Ellis describes one of the challenges astronomers are currently grappling with in "Quest for the first galaxies" (p. 24).

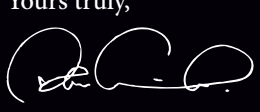
Any study of cosmology requires a look into some of the weird creatures of the universe. Science writer Steve Nadis' "The secret lives of black holes" (p. 30) and "What is dark energy?" (p. 36) bring us up to date on the latest from those areas.

David J. Eicher

The laws that describe how things work in the cosmos also receive scrutiny in this issue. Astronomer C. Renée James of Sam Houston State University explores interactions in "The ugly side of gravity" (p. 42). Steve Nadis describes the most current research on a sticky aspect of cosmology in "Searching for the shape of the universe" (p. 48). NASA astronomer Sten Odenwald poses the question "What if string theory is wrong?" (p. 78), in which he outlines the widespread role the hypothesis plays in explaining how matter behaves. We need to remind ourselves that string theory is as yet an idea!

In sum, cosmology is a fascinating area of science that brings us face to face with the hows and whys of existence. It's really a study of the meaning of it all.

Yours truly,



David J. Eicher
Editor

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COLLECTOR'S EDITION - 2009

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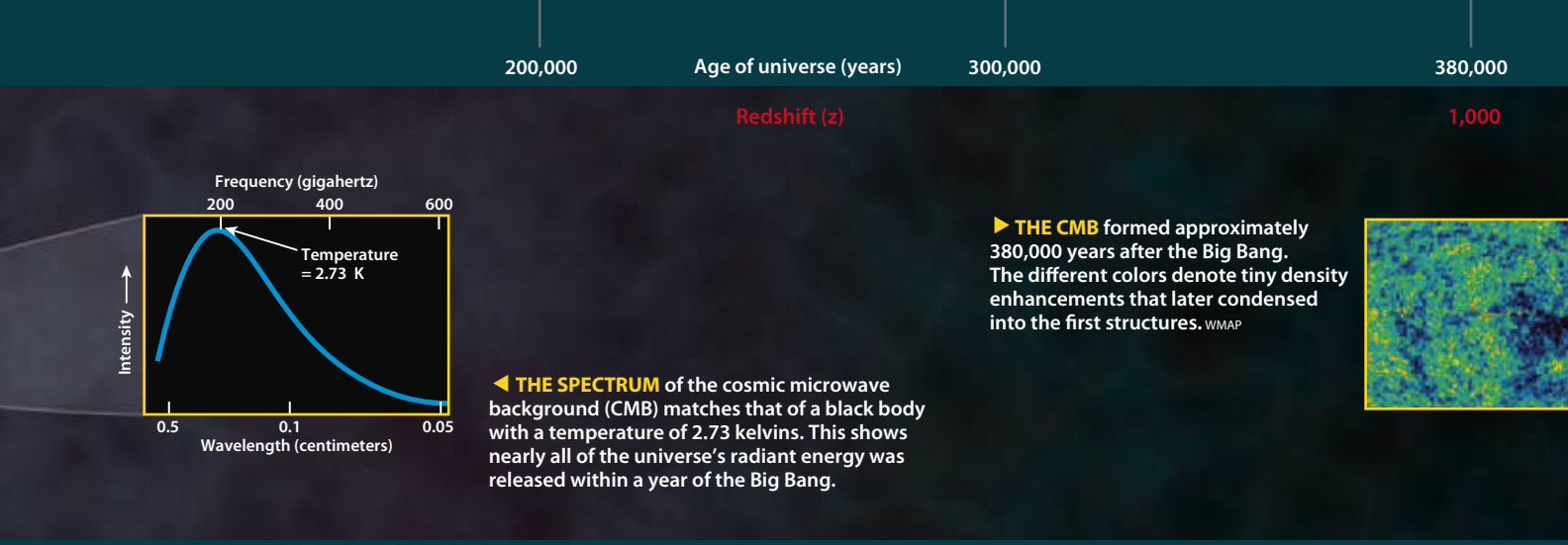
THE BIG BANG marks the birth of the universe, when space, time, and matter came into existence. ALL ILLUSTRATIONS BY *ASTRONOMY*: ROEN KELLY

The first billion years

After the release of the cosmic background radiation, darkness fell over the cosmos. /// **BY ADAM FRANK**



◀ **THE SPECTRUM** of the cosmic microwave background (CMB) matches that of a black body with a temperature of 2.73 kelvins. This shows nearly all of the universe's radiant energy was released within a year of the Big Bang.

▶ **THE CMB** formed approximately 380,000 years after the Big Bang. The different colors denote tiny density enhancements that later condensed into the first structures. WMAP

Big Bang theory tells us the entire universe — all space, time, matter, and dimension — emerged from a single titanic explosion that set the cosmos in motion. Light brilliant beyond description flooded the infant universe.

There's a second part to the scientific story, however, that many people have not heard: Darkness soon returned with a vengeance. The cosmic Dark Ages began less than 1 million years after the Big Bang and lasted for a billion or so years.

For astronomers, the story is still coming into focus as more powerful telescopes and faster computers illuminate the full scope of cosmic history. Using these tools, astronomers are taking their first steps toward understanding the strange universe of the Dark Ages, a cosmos devoid of galaxies that started forming the earliest structures, with starlight shining for the first time.

Adam Frank *is an astrophysicist at the University of Rochester in New York and a member of* Astronomy*'s Editorial Advisory Board.*

Beginning at the beginning

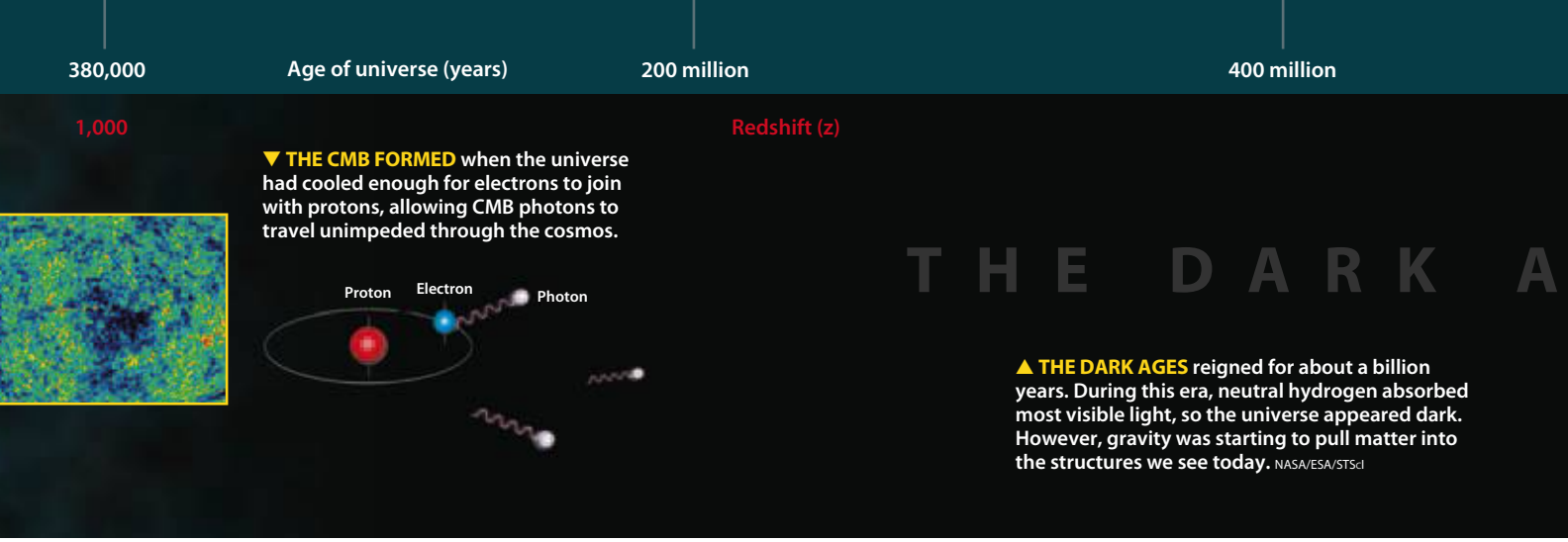
To understand the Dark Ages, we must briefly touch on the first epoch of light: the Big Bang. After this violent birth, the universe was a smooth, hot, dense soup of exotic high-energy particles. Matter and radiation were mixed so closely that they shared a common temperature. In the parlance of physics, matter and radiation were strongly coupled. A photon could cross only a tiny fraction of the universe before being absorbed and then re-emitted by some particle of matter.

Then, as the universe expanded, it cooled, taking the particle-radiation mix through a series of dramatic transitions. They included the creation of protons and neutrons, building blocks of all atomic nuclei, about 1 second after the Big Bang. A scant 3 minutes later, the universe created the lightest nuclei: helium (2 neutrons, 2 protons) and a little lithium (3 protons, 3 neutrons).

During all these changes, matter and radiation remained strongly linked. After about 380,000 years, the universe had expanded and cooled to the point where electrons and protons could catch each other and bind into atomic hydrogen. This was the great parting of ways between matter and light. The birth of atomic hydrogen, the most abundant element in the universe, meant the end of one cosmic era and the beginning of the Dark Ages.

Astronomers often call the era when neutral hydrogen formed "recombination" because electrons and protons combined to form atomic hydrogen. It's a misnomer, however — this is the first time these atoms formed. In most stories of the Big Bang, the emphasis on this era lies with the sudden transparency of the universe to photons and the birth of the cosmic microwave background (CMB). When recombination occurred, photons previously linked to naked electrons and protons found themselves with nothing to interact with. They were free to expand unimpeded with the universe, with their wavelength stretching along with cosmic expansion. We see them today as relics of the Big Bang. If the still-smooth universe became transparent to photons and thus light, why does recombination signal the beginning

THE GOODS SURVEY uses advanced telescopes, including Hubble, Spitzer, and Chandra, to target a fairly empty region of space . The goal is to get a census of the universe and to probe back toward the beginning of cosmic structure. NASA/ESA



▼ THE CMB FORMED when the universe had cooled enough for electrons to join with protons, allowing CMB photons to travel unimpeded through the cosmos.

▲ THE DARK AGES reigned for about a billion years. During this era, neutral hydrogen absorbed most visible light, so the universe appeared dark. However, gravity was starting to pull matter into the structures we see today. NASA/ESA/STScI

of the Dark Ages? The answer lies with visual light, the kind our eyes respond to.

While the neutral hydrogen gas could not absorb cosmic background photons, it efficiently absorbed visual and ultraviolet (UV) light. As soon as neutral hydrogen dominated the universe, visual and UV photons became trapped close to any source producing them. Most of the hydrogen gas in today's universe is "ionized," meaning it consists primarily of bare hydrogen nuclei and free electrons. Stellar UV light maintains this ionization. These photons pack enough punch to tear electrons off any neutral hydrogen atoms that form by recombination. The current dominance of ionized hydrogen is one reason we can see so far with optical telescopes. The Dark Ages were the epoch of cosmic history between the initial formation of neutral hydrogen and its eventual destruction.

What was it, however, that illuminated the universe with the glow we now recognize as starlight? How did the cosmos go from a smooth, dark sea of neutral gas emerging from the recombination era to the multitudes of stars and galaxies that dominate today? The Dark Ages mark an era of transitions, not only from blackness to light, but also from formlessness to form.

The universe at recombination was extraordinarily smooth. From detailed studies of the CMB, astronomers know that any ripples, bumps, and lumps in the density of cosmic plasma were 1/10,000 as small as matter's average density. The universe we live in now bears little resemblance. Today's lumps and blobs — stars and galaxies — are far denser than an average volume of space, which is pretty close to a vacuum. The journey through the Dark Ages takes astronomers through the epoch when tiny, initial bumps, or perturbations, in the cosmic stew first began exerting their gravitational influence, feeding on surrounding gas in an effort to grow into the structures we see today.

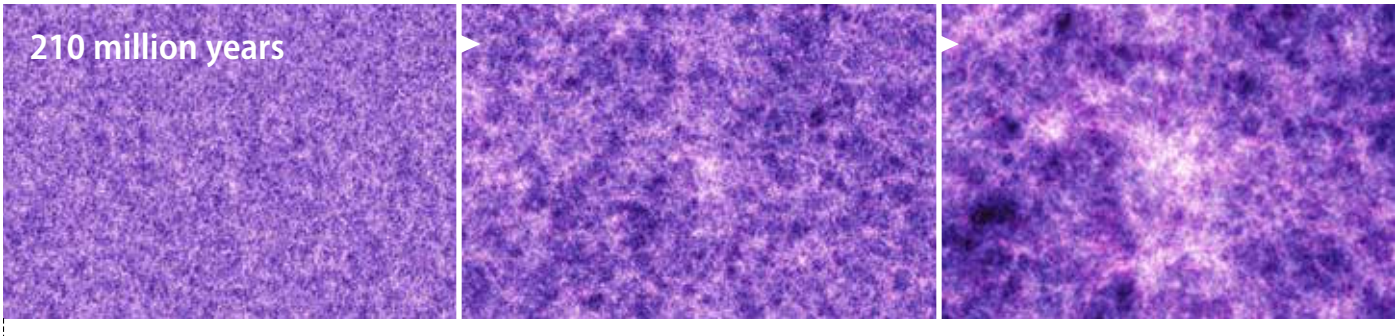
DID STRUCTURE FORM from the top down, or from the bottom up?

"There is tension in the early universe between expansion and collapse," explains Greg Bryan of Columbia University. Working with his former thesis advisor, Mike Norman of the University of California at San Diego, and Tom Abel of Stanford University, Bryan has pioneered using advanced computer simulations to study the formation of the universe's first structures.

In the absence of cosmic expansion, a lump of matter denser than its surroundings will draw in material at an ever-increasing rate. The denser the growing lump gets, the stronger its gravity becomes, and the faster it draws new material inward — a runaway collapse. The expansion of the universe changes this process. Just as gravity tries to draw some over-dense lump together, the universe's expansion pulls it apart.

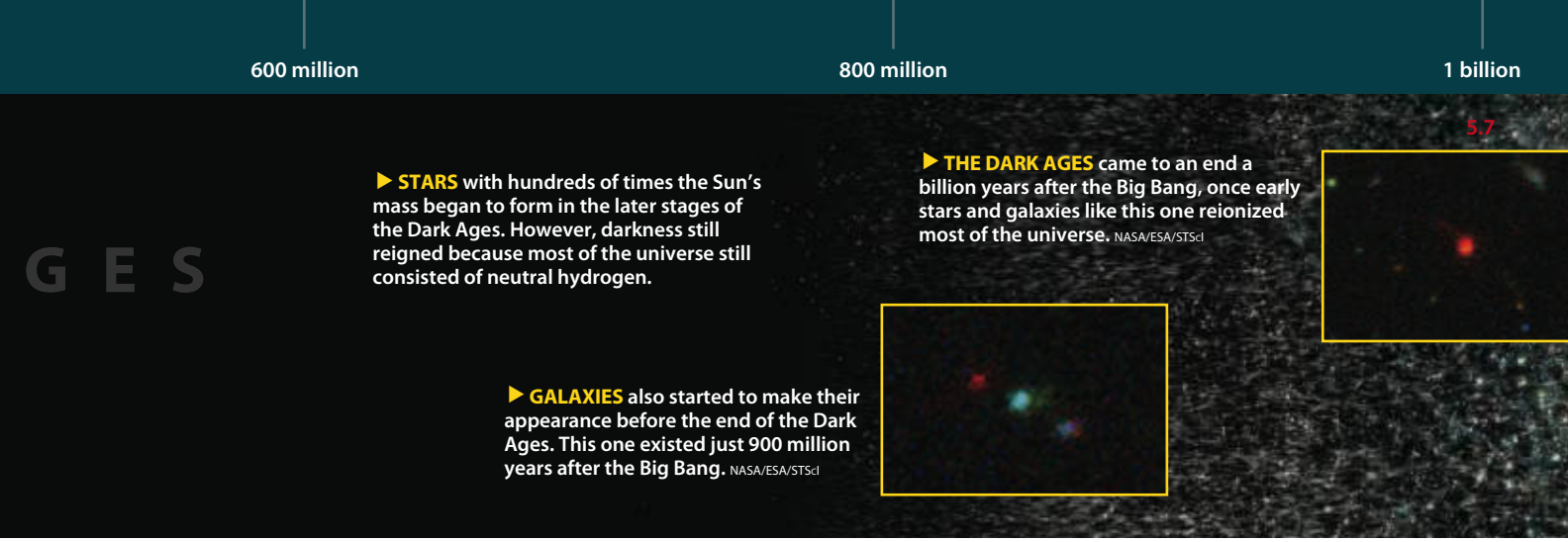
"During the earlier years of cosmological study, this struggle between gravity growing structures and expansion diluting them caused astronomers a lot of consternation," says Bryan. Originally, astronomers had hoped that any perturbation, even one as small as an atom, could grow into a cluster of galaxies. The push-pull of expansion and gravity dashed that hope.

"There needs to be a range of perturbations that already exists at recombination," explains Bryan, "and they need to be large enough to allow gravity to do its work so the structures we see now can emerge."



VOLKER SPRINGEL (MAX PLANCK INSTITUTE FOR ASTROPHYSICS), ET AL.

THE MILLENNIUM RUN simulation tracked 10 billion dark-matter particles to see how cosmic structure formed. This sequence shows the universe at an age of 210 million years (z = 18.3), well within the Dark Ages. Each image left to right zooms in by a factor of 4.


600 million
800 million
1 billion
5.7
▶ STARS with hundreds of times the Sun's mass began to form in the later stages of the Dark Ages. However, darkness still reigned because most of the universe still consisted of neutral hydrogen.
▶ THE DARK AGES came to an end a billion years after the Big Bang, once early stars and galaxies like this one reionized most of the universe. NASA/ESA/STScI
▶ GALAXIES also started to make their appearance before the end of the Dark Ages. This one existed just 900 million years after the Big Bang. NASA/ESA/STScI

Astronomers now understand that while the perturbations seen in the microwave background may be tiny, those bumps — imprinted at the Big Bang's earliest stages — are large enough to give gravity the head start it needed once the Dark Ages began.

Perturbations grew slowly as the Dark Ages progressed. Eventually, the density contrast between a growing lump and its surroundings became obvious, and gravity halted expansion in that region.

Winners and losers

When the cosmic plasma entered the Dark Ages, perturbations imprinted on it from the beginning ranged in size. Some were planet-sized wiggles, and some were vast undulations that stretched across galactic distances. For many years, astronomers did not know which of these wiggles grew fastest. Did structure form from the top down, or from the bottom up?

"You must remember that most of the matter in the universe is dark matter," explains Bryan. Given dark matter's preponderance — it makes up more than 80 percent of the universe's mass — its properties determined how structure formed.

"For many years, people fought between hot-dark-matter and cold-dark-matter models," says Bryan. "Hot" and "cold" in this context mean fast and slow moving. The difference is important because fast-moving dark matter tends to stream out of any small clumps trying to grow. It's a bit like flicking marbles across a flat surface and trying to catch them in shallow depressions. If the marbles move quickly, they barely know the depressions exist. If they roll slowly, they have a better chance of getting trapped.

Hot-dark-matter models need big collections of stuff to form before gravity can make the structure collapse. With hot dark matter, the largest wiggles grew fastest. Smaller clumps formed once the big ones were done — top-down structure formation.

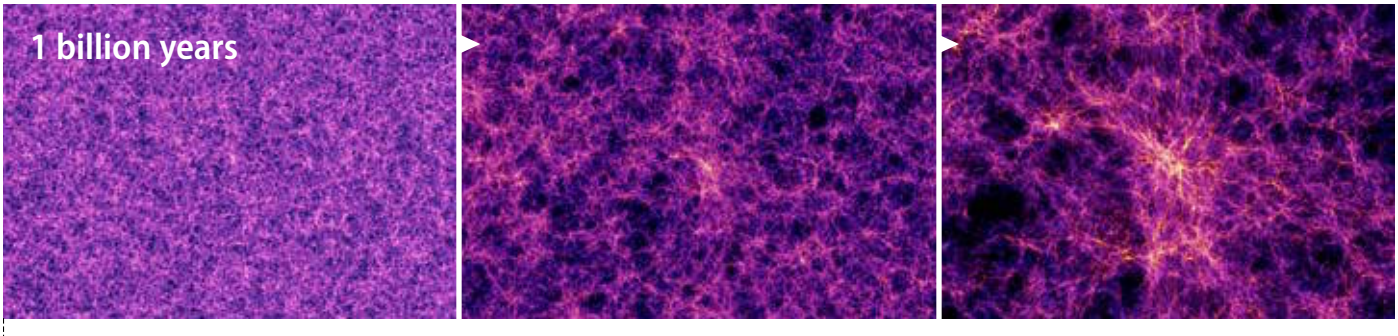
Cold dark matter does the opposite. Little wiggles grew fastest, so structure formed from the bottom up. Once the clumps collapsed, they merged with other small clumps to form ever-larger structures. By the early 1990s, astronomers had ample evidence that only cold-dark-matter models could produce the kinds of structures we see in the current universe. "The cold-dark-matter models won because they compared better with observations," says Bryan.

According to Bryan, the first objects to become gravitationally bound may have been Earth-sized clumps of dark matter. But while the clump might have been about Earth's size, it would have been tenuous — at best a dark-matter ghost of a planet.

Dark clump to bright star

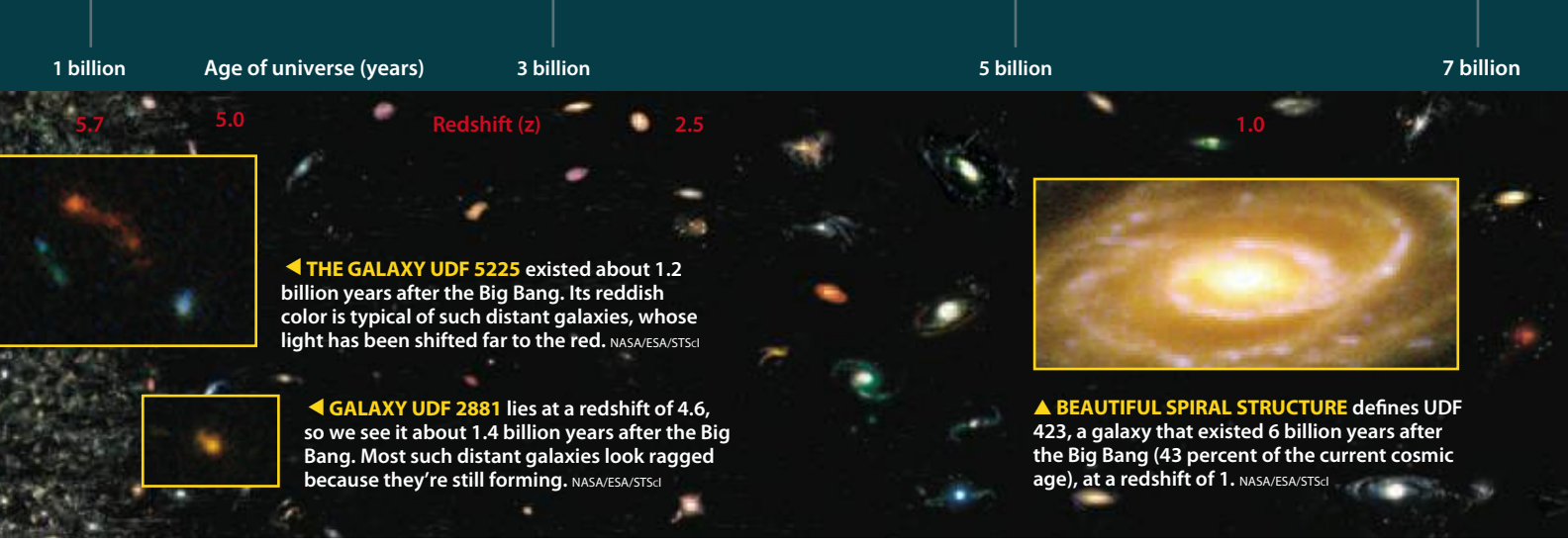
In today's universe, a giant halo of dark matter surrounds the visible part of every galaxy. Astronomers also use the term *halos* for the first dark-matter structures to form. At a redshift around z = 60, the dark matter halos had grown to contain almost 1,000 times the Sun's mass. Ordinary matter had not yet joined the party. The 1,000 solar masses were too little to cause ordinary matter, mostly hydrogen gas, to clump. While dark matter began to form significant structures, ordinary gas was still too hot and moving too fast to be contained in the shallow gravity wells of nascent halos.

Only when the dark matter halos grew to 10,000 times the Sun's mass could the hydrogen clump, too. The first clumping of ordinary matter — our kind of stuff — marked a critical moment in cosmic history. Unlike dark matter, normal (or "baryonic") matter can dissipate its energy. In other words, it can cool and slow down, which allowed hydrogen and helium to condense at the center of a growing dark matter halo.



VOLKER SPRINGEL (MAX PLANCK INSTITUTE FOR ASTROPHYSICS), ET AL.

THE DARK AGES CONCLUDED about 1 billion years after the Big Bang (z = 5.7). At this time, the first stars — massive beasts weighing more than 100 solar masses drawn together by cold dark matter — already had formed. Galaxies were just starting to form.



◀ **THE GALAXY UDF 5225** existed about 1.2 billion years after the Big Bang. Its reddish color is typical of such distant galaxies, whose light has been shifted far to the red. NASA/ESA/STScI

◀ **GALAXY UDF 2881** lies at a redshift of 4.6, so we see it about 1.4 billion years after the Big Bang. Most such distant galaxies look ragged because they're still forming. NASA/ESA/STScI

▲ **BEAUTIFUL SPIRAL STRUCTURE** defines UDF 423, a galaxy that existed 6 billion years after the Big Bang (43 percent of the current cosmic age), at a redshift of 1. NASA/ESA/STScI

This was the moment when the universe's first star was poised to form.

To make a star, matter must collapse into the bottom of a gravitational well. The more gas that falls into the well, the higher the density. Eventually, nuclear fusion occurs, and the star turns on.

Astronomers understand how stars form in the current cosmos and know enough to paint the outline for forming the first generation of stars. Life in the Dark Ages was not that simple, however. In astronomers' quest to comprehend the births of the first stars, they have been thrown many curveballs.

"The absence of heavy elements is the most important difference between modern star formation and the creation of the first stars," explains Bryan. Astronomers call every element more massive than helium a metal. And metals are, for the most part, created inside stars. Metals in an astrophysical gas can shed heat far more efficiently than hydrogen or helium atoms. The photons emitted by metals stream out of the gas, taking energy with them. In this way, even traces of metals can act as highly effective refrigerants.

The first stars, however, formed from gas lacking metals. This primordial gas had almost no way to cool. "The cooling is very slow until hydrogen atoms combine to form hydrogen molecules," says Bryan. He also points out that molecular hydrogen in the modern universe forms on dust grains, which are made of metals. Without dust, molecular hydrogen formed so slowly that dark matter halos grew to a million solar masses before ordinary matter could really begin to cool. "These dark matter halos are literally microgalaxies, one-millionth the mass of a present-day galaxy, by the time the first star can begin to form," says Bryan.

THE UNIVERSE'S FIRST stars may all have been hundreds of solar masses.

The wait leads to disappointment on a cosmic scale. According to Bryan's calculations, the type of star that finally contracts from the primordial gas is a kind of monster rarely seen in the current universe.

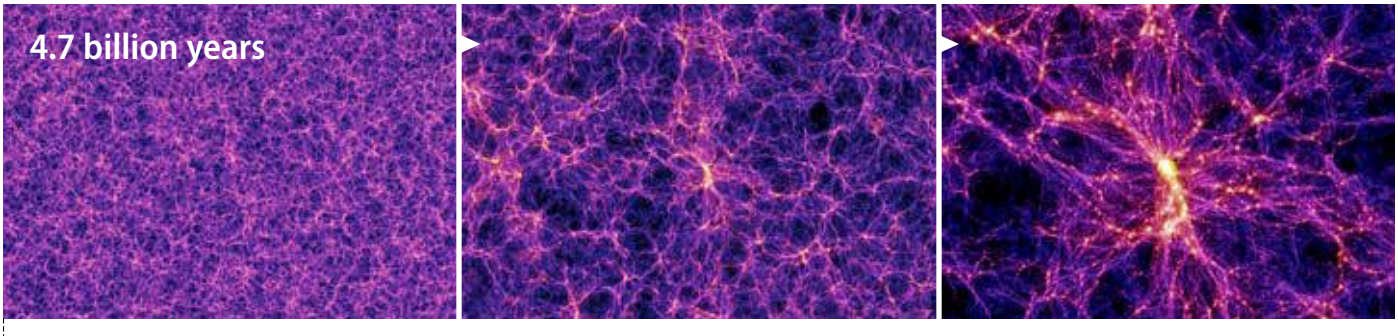
In today's cosmos, any star larger than 8 solar masses is considered massive and has a harder time forming than its smaller cousins. Stars more than 100 times the Sun's mass are so rare that we know of only a handful in the entire Milky Way.

A giant's birth and death

According to Bryan, the universe's first stars may all have been this big. Over the past several years, Bryan, Norman, and their collaborators have used advanced computer simulations to track the evolution of cosmic structure from the era of recombination to the formation of the first star. Unlike traditional simulation methods, Bryan's code simultaneously tracks a huge range of scales, everything from vast arcs of still-forming dark matter halos millions of light-years across down to the outlines of the first star with a radius just a few times that of Earth's orbit.

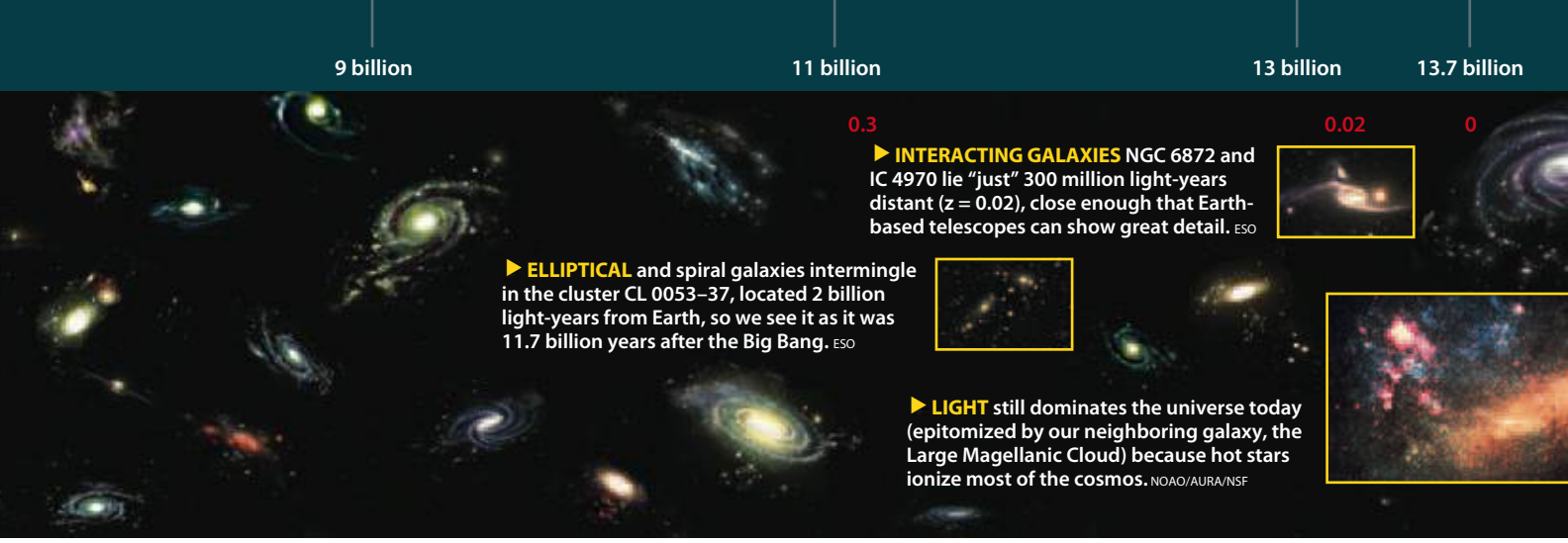
After running the codes continuously for years, the researchers found that each microgalaxy halo produces exactly one massive star. Each star weighs a few hundred solar masses. But the story doesn't end there. Massive stars burn hot and die fast. In their brief lives, they dramatically affect their environment.

The massive stars in Bryan's calculations produce a torrent of UV photons that ionize every hydrogen atom out to well beyond



VOLKER SPRINGEL (MAX PLANCK INSTITUTE FOR ASTROPHYSICS), ET AL.

GALAXIES AND CLUSTERS appear prominent by the time the cosmos is 4.7 billion years old (z = 1.4). On the biggest scales (left), the universe still looks fairly smooth, but closer up, individual galaxies and clusters start to dominate.


9 billion
11 billion
13 billion
13.7 billion
0.3
0.02
0
▶ INTERACTING GALAXIES NGC 6872 and IC 4970 lie "just" 300 million light-years distant (z = 0.02), close enough that Earth-based telescopes can show great detail. ESO
▶ ELLIPTICAL and spiral galaxies intermingle in the cluster CL 0053–37, located 2 billion light-years from Earth, so we see it as it was 11.7 billion years after the Big Bang. ESO
▶ LIGHT still dominates the universe today (epitomized by our neighboring galaxy, the Large Magellanic Cloud) because hot stars ionize most of the cosmos. NOAO/AURA/NSF

1,000 light-years. "The ionization produced by the big stars heats the surrounding gas and, in the process, can completely unbind all the baryons from the still-forming dark matter halo," explains Bryan. Even worse, when a star this size runs out of nuclear fuel — after only a million years — it ends its life in a titanic explosion that blows away the halo gas.

Only a star bigger than 300 times the Sun's mass can escape this fate. Such hypergiant stars may implode as a black hole without ever exploding.

From darkness to darkness

Although the massive stars that form in Bryan's simulations ionize lots of gas, they don't pack enough punch to alter the balance of neutral-to-ionized hydrogen atoms completely. The universe remains dark. "We really don't know what happens next," declares Bryan. "Does the next generation of stars form in blast waves from first-generation supernovae?" Bryan and other astronomers now are focusing their efforts on the era when the Dark Ages ended — sometime between redshift 17 and approximately redshift 6.

"We know that the growing dark matter halos create objects that probably look like today's dwarf galaxies," says Bryan. On the baryon side of the equation, successive stellar generations eventually created enough metals to bring the star-formation process in line with what we see today. At that point, stars of all masses can form.

Still, astronomers have yet to fill in the details, and many of our current ideas may be wrong. For example, no one knows what role black holes played in re-ionizing the universe. Any black hole that formed during this epoch would have drawn in gas at a prodigious rate. As the gas fell toward the black hole, it emitted ionizing UV photons.

"People used to think that re-ionization and 'first light' occurred quickly, at a redshift of around 6 or 7," says Bryan. "These days, that is not so clear." Did black hole accretion effectively contribute to filling the universe with visible light? How did the galaxy-formation process continue to the point of building the great spirals and ellipticals we see today? Answers to these questions remain unknown.

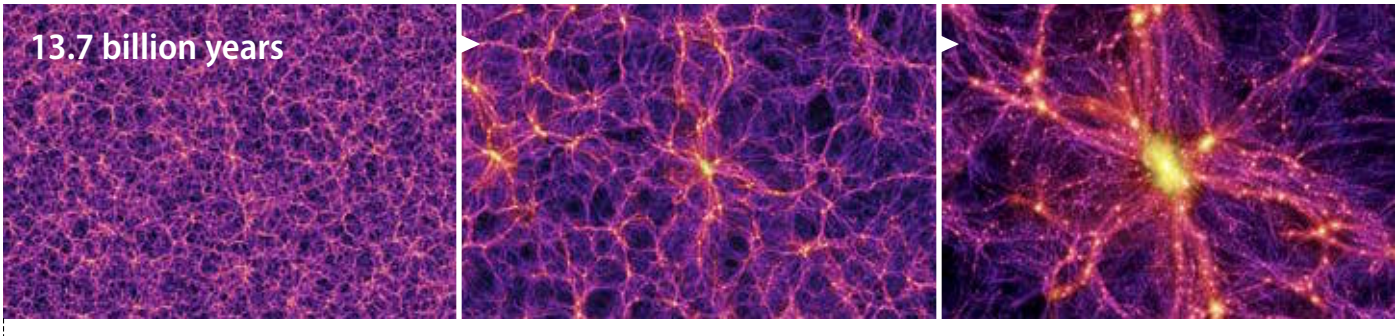
Seeing first light

While questions concerning the first billion years abound, hope for answers does as well. An array of new instruments, scheduled to come online during the next decade or two, holds the promise of directly probing the Dark Ages and its end in the era of re-ionization.

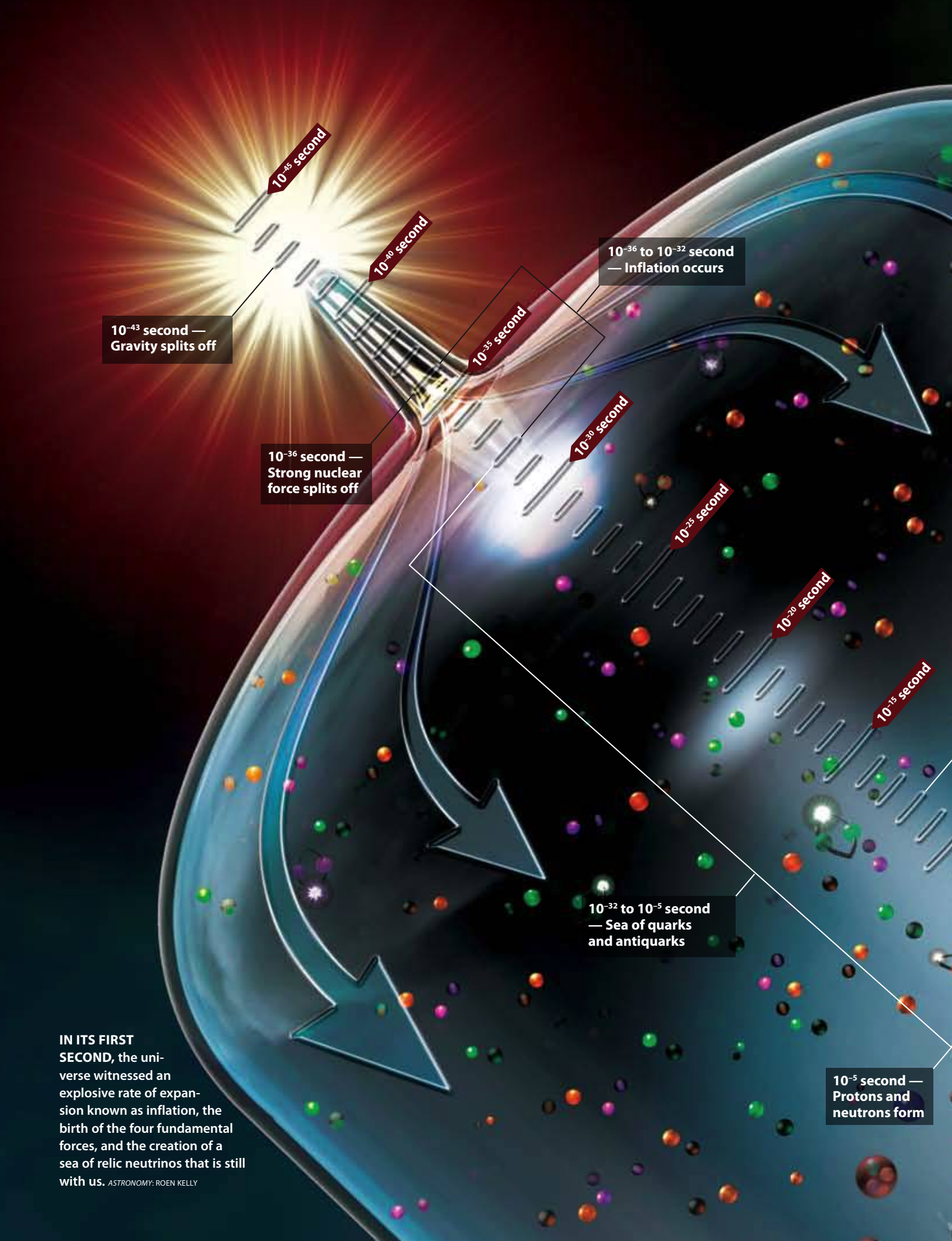
The highest profile instrument will be Hubble's successor: the James Webb Space Telescope (JWST). Ultraviolet and visible light emitted during the era of re-ionization now has been redshifted to the infrared. With a 6.5-meter mirror and high sensitivity in the infrared, JWST will explore the nature of the objects that lit up the universe at the end of the first billion years.

In addition, astronomers hope the Square Kilometer Array will directly probe radio waves emitted by clumps of atomic hydrogen gas during the Dark Ages. The ability to map ripples in gas density at such early times and far-flung distances could prove to be a watershed. Astronomers would get their first clear view of the early universe's initial structures.

From light to darkness to light again — this describes the unveiling of our universe's early years. By illuminating the Dark Ages, the age of first structures and massive primeval stars, astronomers are exploring a critical gap in cosmic history. With only the outlines filled and much still to be written, there can be no doubt we live in our own privileged epoch.



IN TODAY'S UNIVERSE, rich galaxy clusters follow filaments of dark matter, with large voids separating the denser regions. Ordinary matter now largely follows the lead established by dark matter, and dark matter halos surround individual galaxies.


10^{-45} second
10^{-40} second
10^{-43} second — Gravity splits off
10^{-36} to 10^{-32} second — Inflation occurs
10^{-35} second
10^{-36} second — Strong nuclear force splits off
10^{-30} second
10^{-25} second
10^{-20} second
10^{-15} second
10^{-32} to 10^{-5} second — Sea of quarks and antiquarks
10^{-5} second — Protons and neutrons form

IN ITS FIRST SECOND, the universe witnessed an explosive rate of expansion known as inflation, the birth of the four fundamental forces, and the creation of a sea of relic neutrinos that is still with us. *ASTRONOMY:* ROEN KELLY

The Big Bang + 1 second

The birth of the universe released a torrent of neutrinos. Where are they?

/// **BY STEVE NADIS**

10^{-12} second — Electromagnetic and weak nuclear forces split
10^{-10} second
10^{-5} second
1 second
1 second — Cosmic neutrino background forms

Astronomers who study the early universe divide into two camps: theorists and observers. Theorists routinely work on ideas like inflation, which began some 10 trillion-trillion-trillionths of a second after the Big Bang. Observers, on the other hand, hit a roadblock if they try to look back further than 380,000 years after the Big Bang — when photons of light were first set free and created the cosmic microwave background (CMB).

Nonetheless, observers may have one path to take them back further. The Big Bang created a flood of neutrinos — subatomic particles that rarely interact with matter — that should fill the universe with an estimated 300 neutrinos per cubic centimeter, producing a background like the CMB. And those primordial, or "relic," neutrinos date back to a mere second after the Big Bang.

No one has detected a relic neutrino, which by now would have cooled to a frosty 1.95 kelvins, although scientists have pondered the problem for decades. The chief difficulty is that neutrinos are

Contributing Editor **Steve Nadis** *is a science writer living in Cambridge, Massachusetts. He enjoys writing about cosmology and the early universe.*

NEUTRINO PRIMER

ANISOTROPY
A lack of uniformity in, say, the cosmic background, seen when looking in different directions.

COBE
The Cosmic Background Explorer, a NASA satellite launched in October 1989 that made detailed measurements of the background radiation.

COSMIC MICROWAVE BACKGROUND
The cooling afterglow of cosmic genesis, released about 380,000 years after the Big Bang at the time when matter and radiation parted ways.

COSMIC NEUTRINO BACKGROUND
The flood of neutrinos cosmologists suspect was released 1 to 2 seconds after the Big Bang.

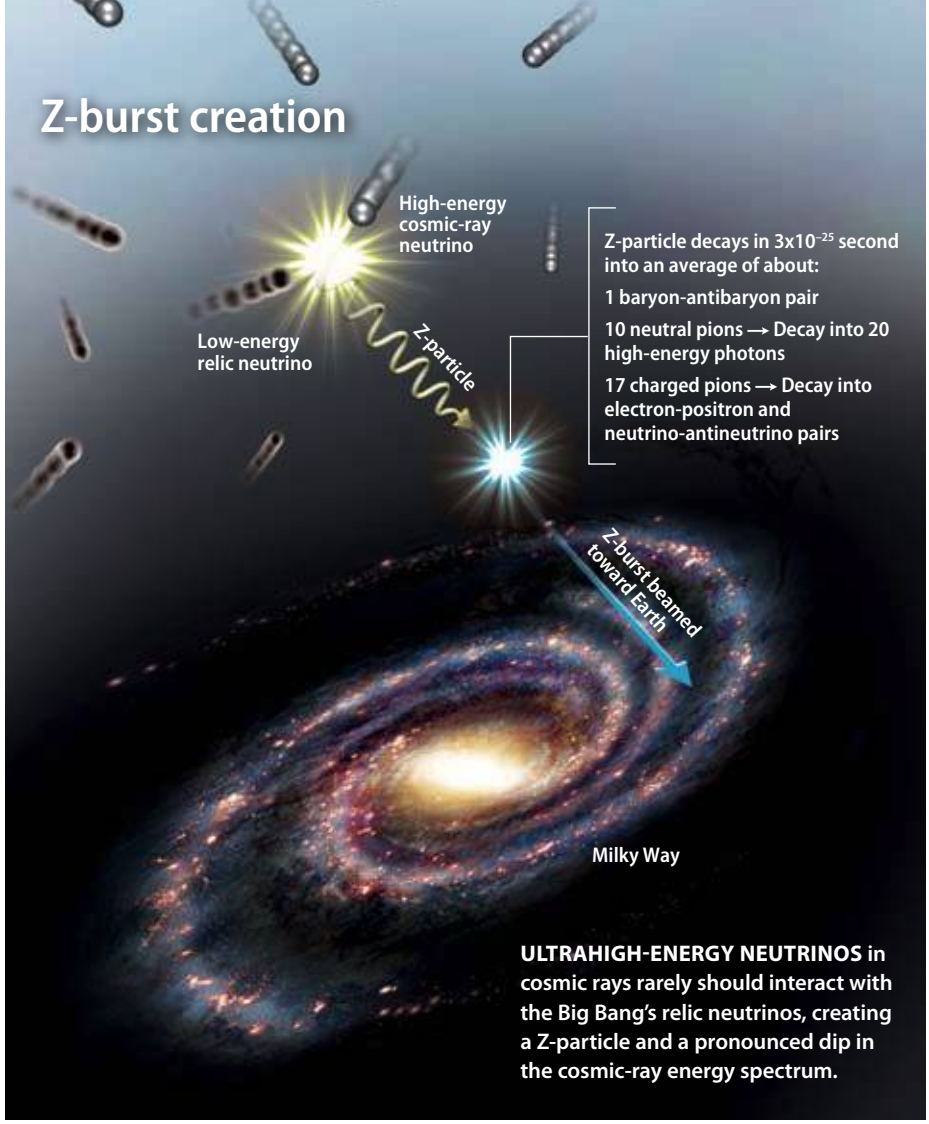
COSMIC STRINGS
One-dimensional defects in the structure of space-time.

DOMAIN WALLS
Two-dimensional defects in the structure of space-time.

GRAND UNIFICATION THEORY (GUT)
A theory that combines electromagnetism, the strong nuclear force, and the weak nuclear force.

INFLATION
A period of rapid expansion that took place 10^{-36} second after the Big Bang.

MAGNETIC MONOPOLES
Hypothetical particles that contain only one magnetic pole.


Z-burst creation
High-energy cosmic-ray neutrino
Low-energy relic neutrino
Z-particle
Z-particle decays in 3x10⁻²⁵ second into an average of about:
1 baryon-antibaryon pair
10 neutral pions → Decay into 20 high-energy photons
17 charged pions → Decay into electron-positron and neutrino-antineutrino pairs
Z-burst beamed toward Earth
Milky Way

ULTRAHIGH-ENERGY NEUTRINOS in cosmic rays rarely should interact with the Big Bang's relic neutrinos, creating a Z-particle and a pronounced dip in the cosmic-ray energy spectrum.

ASTRONOMY: ROEN KELLY

▲ THE MOON is being targeted by GLUE — the Goldstone Lunar Ultra-high energy neutrino Experiment. Scientists hope to see flashes as neutrinos explode in the lunar soil.
T. A. RECTOR/I. P. DELL'ANTONIO/NOAO/AURA/NSF

◀ THE 70-METER GOLDSTONE radio telescope looks for neutrinos crashing into the Moon. It hasn't found any. NASA/JPL

elusive by nature, even under the best circumstances, and their interactivity decreases with the square of their energy. After cooling for nearly 14 billion years, Big Bang neutrinos would pass through virtually everything without a trace. In the unlikely event that a cold neutrino did react with one of the traps astronomers have laid, the resulting signal would be "frustratingly minuscule," according to University of Hawaii physicist John Learned.

Thomas Weiler of Vanderbilt University realized in 1982 that astronomers needed a different approach — something that went beyond conventional neutrino searches. Suppose some neutrinos are flying around at ridiculously high energies, roughly a billion times greater than our best particle accelerators can achieve. There is a special energy at which the probability of this hyperkinetic neutrino interacting with a cold relic neutrino (or antineutrino) goes way up. This occurs at the resonant energy of the Z-particle, which is the product of this neutrino-antineutrino collision.

THE ANITA-LITE EXPERIMENT flew over Antarctica (with Mount Erebus in the background) aboard a scientific balloon in 2003. The experiment looked for high-energy neutrino interactions with the ice. It came up dry. NASA

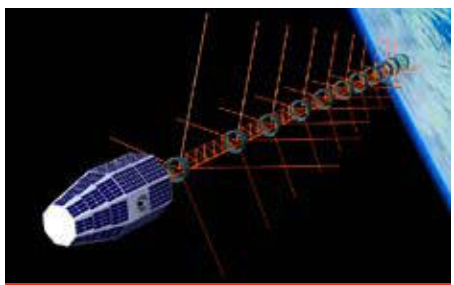
To make a Z-particle, the fast-moving neutrino would need some 10^{22} to 10^{23} electron volts (eV) of energy before slamming into its relatively inert counterpart. Anyone lucky enough to witness lots of these events would notice a dip at the Z resonance level — the energy at which the Z-particle is produced. Observing such a "Z-dip," as Weiler calls it, would confirm a cosmic neutrino background that parallels the CMB — and predates it by 380,000 years.

But the technique would yield another important benefit: Physicists could calculate the neutrino mass because it is dictated by the Z resonance energy (already firmly established) and by the measured absorption energy. With this new data, physicists could, in principle, calculate the masses of the three known neutrino types — electron, muon, and tau — by identifying three separate dips.

In this way, Weiler says, we could compute the neutrino spectrum, just as investigators determine atomic spectra by shining a light on atoms and seeing dark lines at wavelengths where electrons absorb energy. Z-particles decay in a fraction of a second to make new forms of cosmic rays — protons, neutrons, and pions — that decay, in turn, to make gamma rays and neutrinos. The hope is that Earth-based observatories might pick up some of these "Z-bursts" if they originate relatively nearby.

Weiler knew from the onset that two incredible things had to happen for his scheme to work. The first requirement, that neutrinos have mass, has been borne out in experiments since his original paper was published. The second prerequisite, that neutrinos are somehow accelerated to tremendous energies, is contingent on as-yet-unobserved physics. Researchers have proposed two sources for ultrahigh-energy neutrinos. The first is the decay of so-called topological defects. These hypothetical entities — such as cosmic strings, domain walls, and magnetic monopoles — are like defects seen in ice and other crystals and pack lots of energy into a small space. The second possibility is the decay of heavy (and still theoretical) particles created when the universe was ultrahot.

The requirement for exotic sources, whose existence has not been verified, makes the proposition a long shot, Weiler concedes. No cosmic rays have ever been detected with energies much above 10^{20} eV,



THE FORTE (Fast On-orbit Recording of Transient Events) satellite observed Greenland in the late 1990s. It looked for lightning bolts in the ice cap created by the impact of a high-energy neutrino. It had no success. LOS ALAMOS/SANDIA/DOE

yet he's speculating about particles accelerated to energies 100 to 1,000 times greater. Scientists will need a new generation of neutrino and cosmic-ray detectors to confirm this conjecture, along with lots of luck.

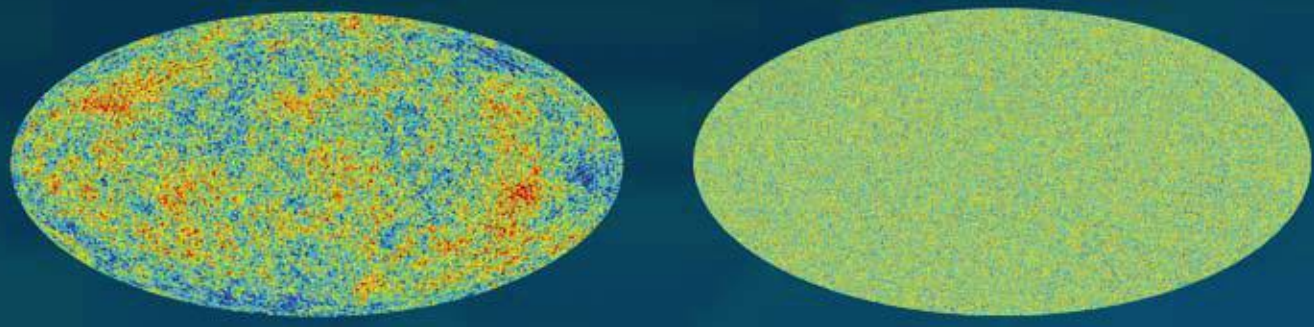
Yet the payoff would be great. The CMB offers a glimpse of the universe when it was 380,000 years old. That's when the Big Bang photons decoupled from what had been an ionized plasma and started streaming freely. Neutrinos, which interact much more weakly than photons, decoupled from matter and radiation when the universe was just a second or two old. "The neutrino background would enable us to look much farther back than the CMB, offering a direct probe of the universe 1 second after the Big Bang," says Andreas Ringwald, a physicist at DESY in Hamburg, Germany.

Fluctuations in the neutrino background, formed when the universe was much smaller and denser, would be on correspondingly smaller scales than the fluctuations observed in the CMB. This would afford scientists new insights on inflation and the initial conditions that led to structure formation. Relic neutrinos are also thought to have played vital roles in nucleosynthesis and the universe's general evolution. "Learning about the physics of the universe at 1 second," says Princeton University's David Spergel, "could tell us about the strength of gravity, for example, while placing interesting constraints on the number of particles created."

The contribution to fundamental physics could be immense, claims MIT cosmologist Max Tegmark. "Information about the number of neutrinos and their masses is the final frontier of the standard model of physics. It's the big unknown — the one thing that hasn't been well-measured."

"The cosmic neutrino background is a profound prediction of Big Bang theory and a very frustrating one," adds University of Hawaii physicist Peter Gorham. "It's like nature's joke on us: Here's something that must exist, but you may never get to see it." On the other hand, Gorham admits, "There's no physical reason why there shouldn't be ultrahigh-energy particles, so it makes sense to look."

Searching for a neutrino signature



THE COSMIC MICROWAVE BACKGROUND (CMB) appears to show the subtle imprint of relic neutrinos. A simulation of the CMB with neutrinos (left) matches what WMAP observed. The net effect of the neutrinos (right) is small. OXFORD UNIVERSITY

He has, in fact, looked for these particles in what might seem to be the unlikeliest places: the Moon, Greenland, and Antarctica. In 2003, Gorham and his colleagues reported on the Goldstone Lunar Ultra-high energy neutrino Experiment (GLUE). The team trained the Goldstone radio telescope in California on the Moon to look for explosions resulting from super-energetic neutrinos (about 10^{21} eV) slamming into it. Such a collision would release an enormous amount of energy in the form of relativistic electrons that would, in turn, create a flash of light. "The burst would be so intense that for 1 nanosecond, it would be brighter than the brightest quasar," explains UCLA physicist David Saltzberg, the project's lead researcher. But nothing like this was seen.

Gorham and other researchers looked for the effects of an ultrahigh-energy neutrino shower on the Greenland icecap, drawing on data collected by the FORTE (Fast On-orbit Recording of Transient Events) satellite from 1997 to 1999. An impact of this sort would have created a 10-meter-long lightning bolt inside the ice and an attendant radio pulse. But again, the team failed to identify such an event.

A 2004 balloon experiment over Antarctica called ANITA-LITE — a prototype of the more ambitious ANITA experiment that lifted off in December 2006 — also came up dry.

The three experiments, Gorham contends, rule out supercharged neutrinos as the main source of the most energetic cosmic rays. In the 1990s, Weiler had proposed that collisions between neutrinos and anti-neutrinos in our galaxy's halo would cause Z-bursts that could unleash the highest-energy cosmic rays ever detected on Earth. The origin of these cosmic rays remains one of the great mysteries of science because ordinary cosmic rays can't travel far without losing energy through interactions with CMB photons.

Weiler proposed that neutrinos could travel unfettered across the universe, creating these cosmic rays relatively nearby through the Z-burst mechanism. "But our results show there would not be a high enough flux of ultrahigh-energy neutrinos to make those cosmic rays," Gorham says.

PLANCK, a spacecraft launched in May 2009, will examine the cosmic microwave background in unprecedented detail. It seeks further evidence of the neutrino background. ESA

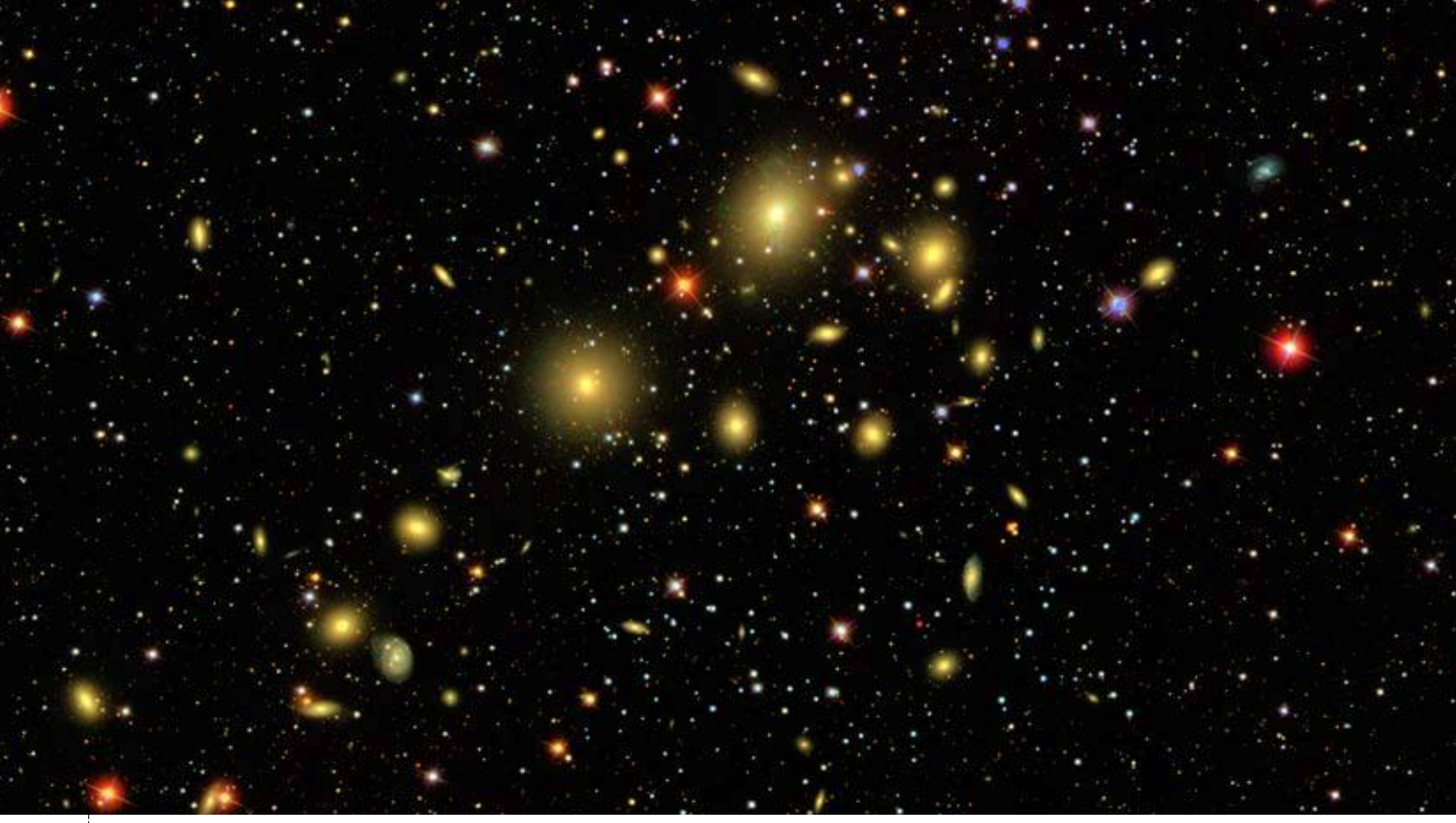
"Of course, we have not ruled out the Z-burst process itself, which might still be the best way of directly observing the cosmic neutrino background."

"While Tom Weiler's Z-burst idea is very cool, we don't know whether neutrinos get accelerated to high enough energies to make it happen," comments FermiLab astrophysicist Scott Dodelson. Fortunately, he says, there are indirect ways of studying relic neutrinos — an approach he compares to "seeing how the needle disturbs the haystack, without seeing the needle itself."

The idea is to look for the imprint of the neutrino background on the CMB, on galaxy distribution (as seen, for instance, by the Sloan Digital Sky Survey), and on the more general distribution of mass revealed by gravitational-lensing experiments. "The CMB is like money in the bank," Dodelson says. "We've done these experiments for more than a decade, and they've always delivered more than expected. Those studies, combined with galaxy surveys and lensing experiments, offer a powerful suite of techniques and the surest way of getting at the neutrino background."

Drawing on WMAP findings released in March 2006 and on large-scale structure and supernova data, Steen Hannestad, a physicist at the University of Aarhus in Denmark, claims to have seen the imprint of relic neutrinos on the CMB with better than 99.99 percent confidence. The effect is subtle, Hannestad explains, "But if the [relic] neutrinos weren't there, you'd see a completely different temperature anisotropy pattern in the CMB." Because neutrinos constituted about 40 percent of the energy density in the early universe — putting them almost on a par with photons — they contributed to the expansion of the universe. However, they did not make a comparable contribution to structure formation, which has a pronounced bearing on the temperature pattern observed in the microwave background.

In a 2005 paper published in *Physical Review Letters*, Roberta Trotta of Imperial College London and Alessandro Melchiorri of the University of Rome carried the analysis a step further. "Not only can we detect



THE PERSEUS GALAXY CLUSTER is a rich collection of galaxies imaged by the Sloan Digital Sky Survey. Astronomers who map the distribution of galaxies in the universe expect to see the imprint of the cosmic neutrino background. ROBERT LUPTON AND THE SDSS CONSORTIUM

the sea of [Big Bang] neutrinos, we can also detect the fluctuations, or wiggles, on top of that sea," Trotta says. These neutrino anisotropies have a gravitational effect on the CMB, smoothing out the clumpiness of the early universe on small scales by streaming out of dense regions at essentially the speed of light. "The cosmic neutrino background affects the onset of gravitational collapse," he adds. "If there were no neutrinos, or fewer neutrinos, star formation and galaxy formation would start earlier."

Trotta and Melchiorri ran computer simulations in the absence of neutrino anisotropies and compared the results to actual data from WMAP and the Sloan Survey. Their analysis affirmed the presence of the neutrino anisotropies at the 95 percent confidence level. "We hope to learn more about the neutrino wiggles — not just confirming that the wiggles exist but also determining their structure and distribution," Trotta says. "We're really just at the beginning."

The latest WMAP findings (released in March 2008) nearly cement the case for the cosmic neutrino background. The data confirm its existence to a confidence level of better than 99.5 percent. The neutrinos have such a big effect on the CMB that scientists claim they made up 10 percent of the universe 380,000 years after the Big Bang. This compares with the 12 percent contribution from atoms, 15 percent from photons, and 63 percent from dark matter.

Tegmark expects to see rapid progress on this front. By way of comparison, he says, people started looking for fluctuations in the CMB soon after it was discovered in 1963. "But zero progress was made toward a deeper understanding of theory until 1992, when the COBE results were announced," Tegmark says. "It's the same with the neutrino background: Now that the sensitivity has reached the point where we can learn interesting things about it, we'll learn rapidly."

Weiler is glad to see advances in indirect measurements, but he still believes it's important to get direct observations "to make sure what we're seeing really is the neutrino background and not the decay products of relic neutrinos." FermiLab's Dodelson, for instance, has proposed a "neutrinoless universe" scenario in which relic neutrinos annihilated themselves some 10,000 years after the Big Bang, leaving behind a background of other particles. The search for ultrahigh-energy neutrinos now awaits experiments that rely on bigger detector volumes like the full-scale ANITA.

Cosmic neutrino physics may eventually reach the required level of precision, says Ringwald. "It took decades to establish reliable sources of [10^{12} eV] gamma rays, but now there are dozens of known sources. The same could happen with cosmic neutrinos."

Confirmation of Weiler's Z-dip and Z-burst hypothesis would have several profound ramifications. First would be the clear-cut detection of the cosmic neutrino background. Second would be a determination of the neutrino mass. Third would be the observation of physics at the grand unification theory (GUT) scale, pointing to exotic GUT particles or even to more exotic cosmic strings. Each of these would be important, warranting — in the opinion of Gorham and Dodelson — an automatic Nobel Prize.

Rather than getting carried away by dreams, Weiler is mindful of the harsh reality: Although the physics of Z-dips and Z-bursts looks robust, nature still has to cooperate by providing ultrahigh-energy neutrinos from sources that have not yet been identified — and might not even exist. "My 1982 idea may still be the best idea we have for directly detecting relic neutrinos," Weiler says. "But 25 years have passed, and now we need an even better idea."

How the Big Bang forged the

Nuclear reactions in the universe's first minutes made the lightest elements. How it happened laid the groundwork for everything that followed.

/// **BY ADAM FRANK**

THE BIRTH OF DEUTERIUM. The most fragile of the light elements, deuterium (H^2), formed in the universe's first minutes when protons and neutrons stuck together. All astrophysical processes destroy this nucleus, so its abundance has been declining since the Big Bang. Deuterium's absorption feature in the spectra of quasars helps astronomers pin down its original abundance. The fusion reactions illustrated here involve photon emission; other, faster reactions also were present.

ALL ILLUSTRATIONS: *ASTRONOMY:* ROEN KELLY

first elements

Moments after the Big Bang, as the universe quickly expanded from an unimaginably dense, impossibly hot state, something wonderful happened. Over the course of the first 3 minutes, the first elements were born.

Every instant of every day, evidence that the universe began in a cosmic fireball stares us in the face. Proof that the universe was once hot and dense resides in the very atoms from which the stars, planets, and we ourselves are built.

Big Bang nucleosynthesis — BBN, for short — is the field of astrophysics linking the observed abundances of the chemical elements to theoretical predictions based on the Big Bang. Along with the universal redshift of galaxies and the cosmic microwave background, BBN is one of the great pillars on which modern cosmology stands.

BBN is a remarkable mix of precise astronomical observation and exacting physical theory. Using only the abundances of the lightest elements, hydrogen and helium, BBN spins out a detailed picture of our cosmic beginnings. It is a remarkable tale and a grand triumph of science's power and precision. Most amazing of all, the events that drive this story, with consequences stretching across space and time, unfolded in little more than the span of a typical TV commercial break.

Elemental origins

We recognize more than 116 distinct chemical elements today. Each appears different to us — copper is metallic and shiny, while sulfur is yellow and powdery — because the atoms making each element differ. It's hard to believe scientists were still vigorously debating the reality of atoms even 100 years ago. But once researchers confirmed the reality of the atom in the early decades of the previous century, they began probing its internal structure.

Every atom, they found, contains a central nucleus composed of one or more protons, which carry a positive electric charge. Hydrogen, the simplest and most abundant element, has a single proton in its nucleus. It's the number of protons in a nucleus that distinguishes one element from another.

The nucleus also may contain another particle, called a neutron. It's slightly heavier than the proton and lacks an electrical charge. The number of neutrons in a nucleus is what distinguishes one variation of a single element — called an isotope — from another.

A third kind of particle, the negatively charged electron, orbits each nucleus at a great distance. Compared to protons and neutrons, electrons weigh next to nothing. The discovery of atomic, and then nuclear, structure answered questions about the nature of matter that had haunted philosophers and scientists for 2,000 years.

Until the 1930s, physicists could not explain elemental abundances. Why is it so much easier to find hydrogen atoms than, say, iron atoms? And good luck finding a lutetium atom. Hydrogen is vastly more abundant than iron, which is vastly more abundant than lutetium. Why?

In 1937, German-American physicist Hans Bethe (1906–2005) was returning by train to his Ithaca, New York, home following a nuclear physics conference in Washington. It just

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might have been the most productive train ride in history: By using the time to explore equations for the newly developing science of nuclear physics, Bethe discovered the secrets of stellar fusion. Taking into account the high temperatures and densities inferred by astronomers to exist at the centers of stars, Bethe showed how simple elements can be squeezed together to form more complex ones, a process that releases energy.

In a single stroke, Bethe showed how the fusion of elements fuels the stars, that stellar cores are alchemical furnaces transmuting one kind of matter into another. Bethe's success convinced physicists and astronomers that the handiwork of stars could explain all the elements and their abundances.

They were both right and wrong.

In 1957, British astronomers Geoffrey and Margaret Burbidge, American astronomer Willy Fowler, and British astrophysicist Fred Hoyle published a monumental work that put the theory of stellar nucleosynthesis on firm ground. Often known as B^2FH, the paper refined earlier studies into a single coherent picture that accounted for the observed abundances of elements — almost.

While the astronomers could nail down elements like carbon, oxygen, and iron, their model couldn't get the simplest elements right. The theory predicted hydrogen and helium proportions that were completely different from what astronomers observe.

HIDING IN astronomers' journals was a paper that could solve the puzzle, but its solution meant opening a door to the dawn of time.

Stellar nucleosynthesis predicted a cosmos with too little helium. Observations show that helium makes up about 24 percent of the universe's normal matter. Everything heavier accounts for less than 2 percent of the total, and all the rest is hydrogen. For years, astronomers were left scratching their heads at this glaring failure in the midst of a spectacular success.

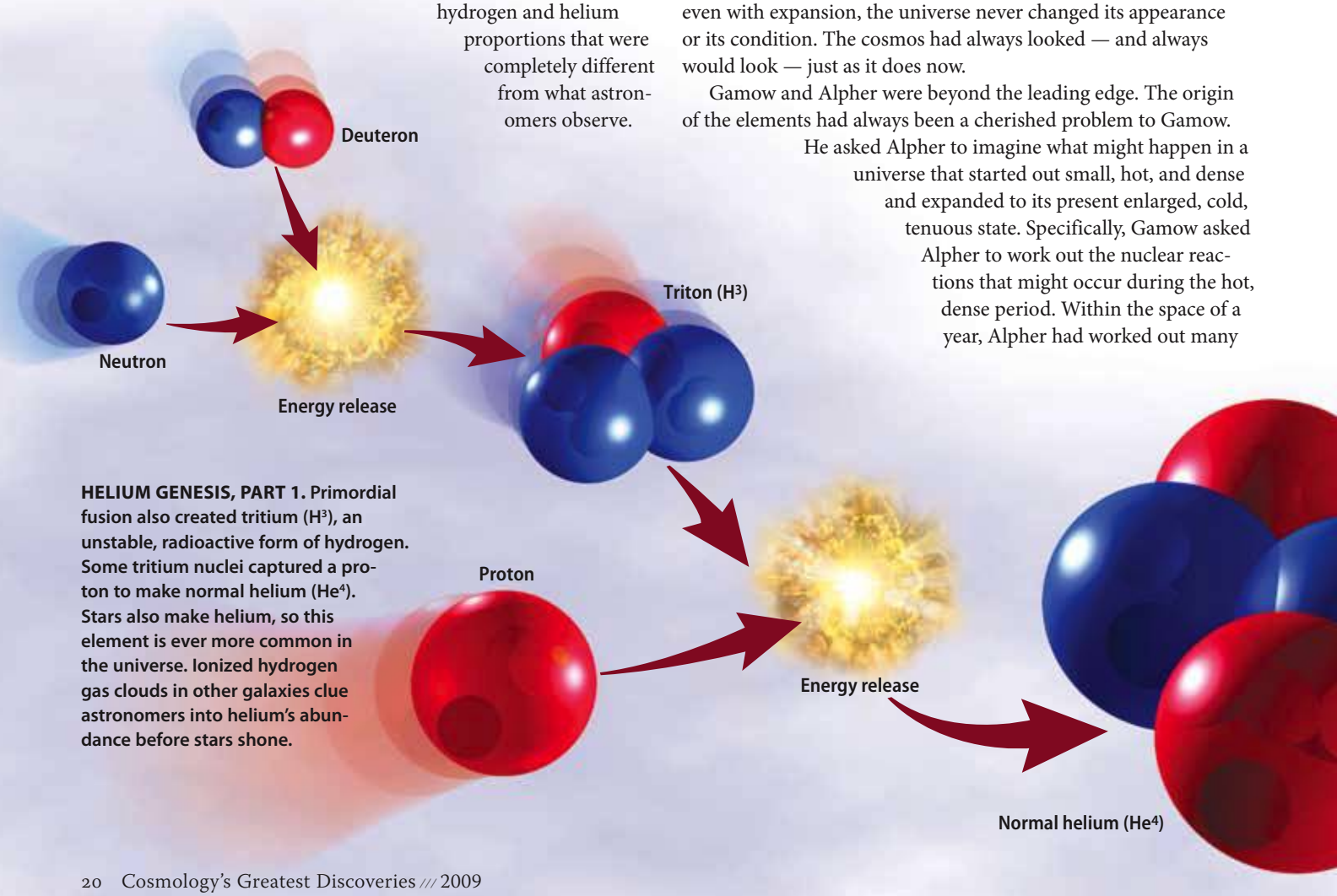
In fact, the answer had already been found and forgotten. Hiding in their journals was a paper that could solve the light-element puzzle. But accepting the solution it offered meant opening a door to the dawn of time.

Beyond steady state

In 1948, Ralph Alpher (1921–2007), a wiry, young graduate from George Washington University, wrote a doctoral thesis that began, for the first time, at the beginning. Under the tutelage of George Gamow (1904–1968), a Russian-refugee physicist known as much for his heavy drinking as for his genius, Alpher set out to describe nuclear physics in the realm of an infant expanding universe.

It's difficult to imagine now how bold, how radical this endeavor was. In 1948, few scientists were thinking about cosmology, and those who were had locked themselves into the so-called steady-state model. Steady-state cosmology held that, even with expansion, the universe never changed its appearance or its condition. The cosmos had always looked — and always would look — just as it does now.

Gamow and Alpher were beyond the leading edge. The origin of the elements had always been a cherished problem to Gamow. He asked Alpher to imagine what might happen in a universe that started out small, hot, and dense and expanded to its present enlarged, cold, tenuous state. Specifically, Gamow asked Alpher to work out the nuclear reactions that might occur during the hot, dense period. Within the space of a year, Alpher had worked out many



HELIUM GENESIS, PART 1. Primordial fusion also created tritium (H^3), an unstable, radioactive form of hydrogen. Some tritium nuclei captured a proton to make normal helium (He^4). Stars also make helium, so this element is ever more common in the universe. Ionized hydrogen gas clouds in other galaxies clue astronomers into helium's abundance before stars shone.

AIP EMILIO SEGRÈ VISUAL ARCHIVES

GEORGE GAMOW, a Russian-American scientist and a pioneer in nuclear physics, suggested the universe originated from a hot sea of radiation and particles.

AIP EMILIO SEGRÈ VISUAL ARCHIVES

RALPH ALPHER and Gamow found that observed abundances of light elements, like hydrogen and helium, are a consequence of a hot, expanding early universe.

NUCLEAR SPEAK

BIG BANG
The event that spawned space, time, and the expanding universe.

DEUTERON
A hydrogen nucleus (proton) bound to a neutron; a nucleus of deuterium.

FUSION
The merger of protons and neutrons to form atomic nuclei, accompanied by a characteristic energy release. The fusion of hydrogen into helium powers the Sun.

NUCLEON
A proton or neutron.

NUCLEOSYNTHESIS
Processes in stars and the early universe that create new atomic nuclei from existing protons and neutrons.

TRITON
A hydrogen nucleus (proton) bound to two neutrons; a nucleus of tritium.

of the crucial aspects with meticulous attention to mathematical detail. It was a triumphant physics tour de force — but one the scientific establishment promptly forgot. While Alpher's first calculations contained some missteps, they got the fundamentals of Big Bang nucleosynthesis correct.

Alpher, along with collaborator Robert Herman, spent the next few years refining his models and examining the implications of a cooling and expanding universe. The team even predicted the presence and temperature of a cosmic microwave background from the redshifted light released when the universe had cooled enough that electrons could combine with nuclei to form atoms.

Alpher said he and Herman expended "a hell of a lot of energy" giving talks to convince astronomers that the results deserved a serious look. But their work received little attention, and, in a tragedy of cosmic proportions, the two physicists ultimately gave up in frustration. Alpher left academia to work for General Electric while Herman moved on to General Motors Research Laboratories.

In the mid-1960s, the weight of new data finally forced the acceptance of Big Bang cosmology. But, even then, Alpher's immense contribution was largely ignored, with credit given almost solely to Gamow.

In the years since, others have refined the picture Alpher and Gamow first glimpsed. Its predictions of simple-element abundances prove that we understand something about cosmic origins. The secret of BBN, the secret Alpher, Gamow, and Herman knew first, occurs just after the cosmos began.

Fusion and the Big Bang

Astronomers see galaxies rushing away from one another in today's expanding universe. But if we could run cosmic evolution backward, everything would draw together. The cosmos would become denser and hotter. As the clock runs backward toward the Big Bang, structures like galaxies melt into a thickening soup of primordial gas. Run the clock back further, and the gas also breaks down into a smooth, ultrahot sea of protons, neutrons, and other subatomic particles. At this point, the universe has a temperature of about 100 billion kelvins. A teaspoon of cosmic matter weighs more than 100,000 tons.

This is where BBN begins. By going back only to about 0.01 second after the beginning, physicists limit themselves to a temperature and density domain they can work with comfortably. More than 60 years of particle accelerator experiments validate their understanding. Running the clock forward from 0.01 second, BBN describes the universe's next 3 minutes in astonishing detail.

From the chaos of those first moments, fusion physics leaves an unalterable imprint on the universe. To choreograph this dance, BBN requires two critical components — an understanding of fusion processes and the physical conditions in the young cosmos.

A hydrogen nucleus (denoted H) is a single proton. Helium nuclei (denoted He^4) have two protons and two neutrons. Fusing hydrogen into helium is a battle between electromagnetism and the strong nuclear force, two of the four forces that govern the cosmos.

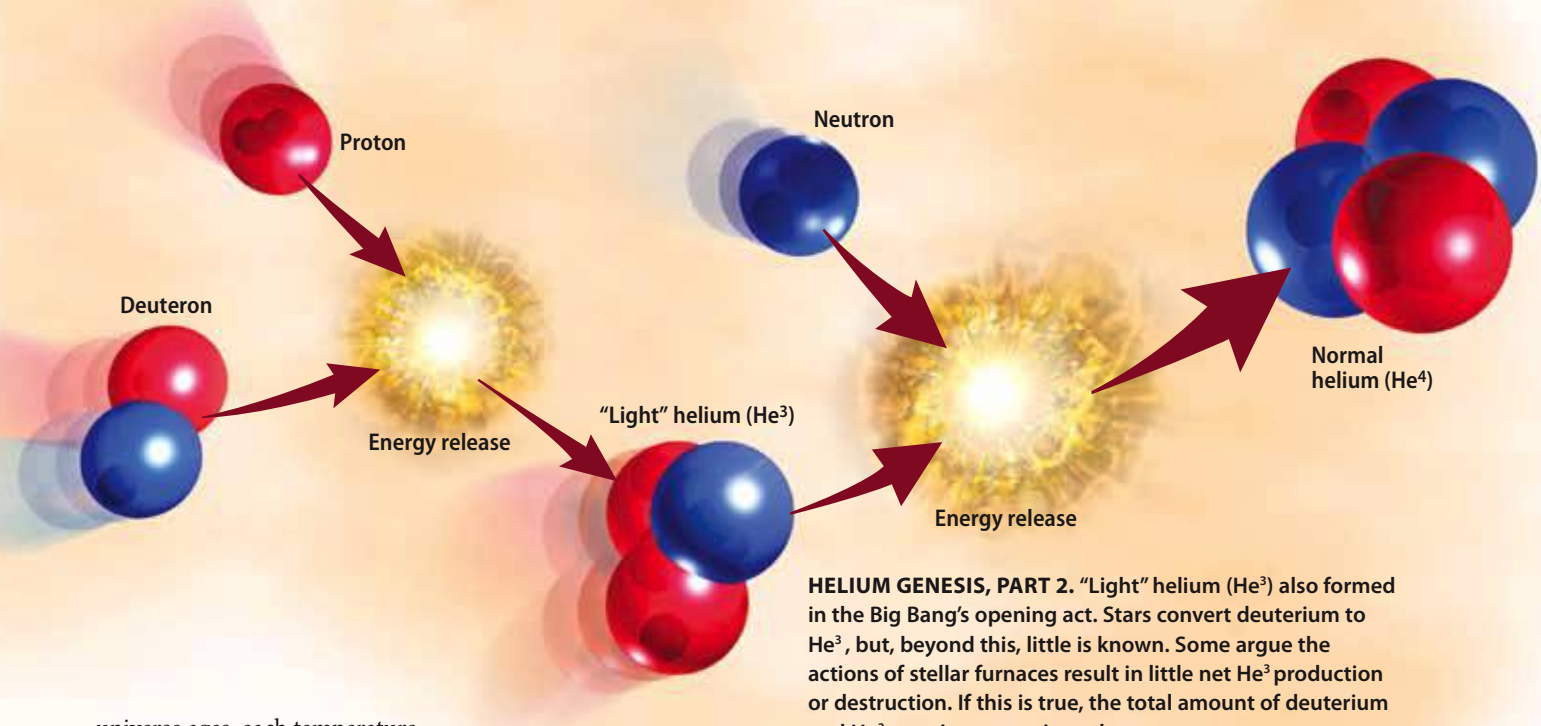
While it's easy to push neutral neutrons together, every proton carries a positive electric charge. Like charges repel via the electromagnetic force, which gets stronger as the particles get closer. (It's like trying to force the same poles of two magnets together.) To fuse into more complex nuclei, protons must overcome this electromagnetic barrier.

The strong nuclear force is more powerful than electromagnetism. But it has the odd property of kicking in only when protons and neutrons get really close to each other.

At a high enough density and temperature, protons whiz around fast enough that some collisions have the energy to push them past the electromagnetic barrier and trigger fusion. But because the universe is expanding and cooling, Big Bang nucleosynthesis becomes a race against time.

Beat the clock

The universe's rapid expansion and cooling leaves only a brief window for nuclear fusion to occur. Einstein's theory of relativity specifies the expansion rate; nuclear physics specifies the temperature and density at each moment in cosmic history. But as the young



HELIUM GENESIS, PART 2. **"Light" helium (He^3) also formed in the Big Bang's opening act. Stars convert deuterium to He^3, but, beyond this, little is known. Some argue the actions of stellar furnaces result in little net He^3 production or destruction. If this is true, the total amount of deuterium and He^3 remains approximately constant.**

universe ages, each temperature and density regime allows only certain particles to exist and certain kinds of reactions between those particles.

Fusion can't start until protons and neutrons — collectively, nucleons — form. A millionth of a second after the Big Bang, when the temperature is a mere 2 trillion K, the universe has cooled enough that quarks can coalesce into protons and neutrons.

About 1 second after the Big Bang, the ratio of neutrons to protons becomes fixed, and fusion reactions can begin. But this window of opportunity lasts only 3 minutes. After this time, the cosmos will have expanded and cooled so much, it won't support fusion reactions at all.

As BBN begins, protons outnumber neutrons 7 to 1. The difference emerges because neutrons are slightly heavier than protons, and this mass difference allows a neutron to decay spontaneously into a proton, electron, and a ghostly particle called a neutrino. Left to its own devices, a lone neutron will, on average, decay into a proton and an electron in just 15 minutes.

Save the neutron

Fusion saved the neutrons. They collided with the abundant protons and fused together as a deuteron — the simplest compound nucleus. A deuteron, a nucleus of deuterium (denoted H^2), is a second stable isotope of hydrogen.

Deuteron formation can't start up in earnest until about 100 seconds after the Big Bang. Once it does, it triggers a cascade of reactions that leads to nuclei with 2 protons and 2 neutrons — helium. For example, a deuteron may collide with a neutron to make tritium (H^3), which then collides with a proton to make normal helium (He^4). Or the deuteron could collide with a proton to make a nucleus of light helium (He^3), which then collides with a neutron to make He^4.

Other reactions create a small amount of lithium and beryllium. But that's as far down the periodic table as we can go before fusion grinds to a halt. More complex elements must await the first stars — several hundred million years in the future.

Scientists must follow all possible reactions, their pace, and all their products. Most importantly, physicists must perform these calculations in a cosmic background of continually changing temperature and density. It is a tremendous task. But when the smoke clears, BBN predicts exactly how much hydrogen, helium, deuterium, and other light elements exist in the cosmos.

FUSION reactions begin about 1 second after the Big Bang and last only 3 minutes.

From H to us

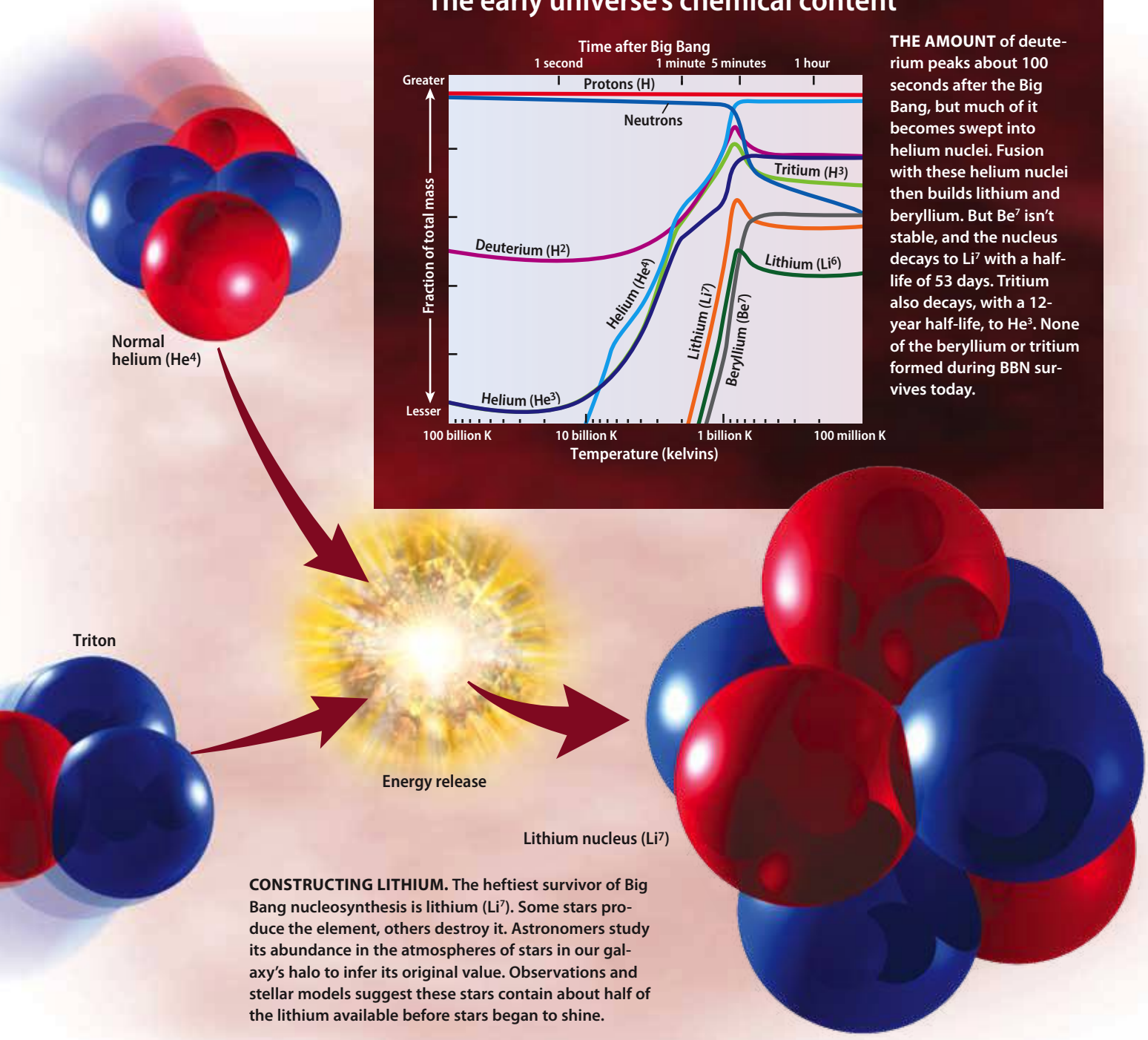
While stellar nucleosynthesis could not match the observation that helium makes up one-quarter of the cosmos' mass, Big Bang nucleosynthesis nails it right out of the gate. BBN's main prediction is the copious early production of He^4. This result ends up being remarkably insensitive to details in the calculation. Barring major changes to the basic scenario, BBN always leads to helium production close to the observed amount. Fundamentally, all that really matters is that a Big Bang occurred.

Helium abundance isn't all that sensitive to conditions in the early universe, but deuterium is another story. The denser the early universe was at the beginning of the fusion era, the more likely it is that all the deuterium would end up in helium nuclei. That some deuterium remains — even 0.01 percent relative to hydrogen — tells physicists something about the young universe.

This and other trace elements let physicists determine the universe's baryonic density — a measure of matter like protons

The early universe's chemical content

THE AMOUNT of deuterium peaks about 100 seconds after the Big Bang, but much of it becomes swept into helium nuclei. Fusion with these helium nuclei then builds lithium and beryllium. But Be^7 isn't stable, and the nucleus decays to Li^7 with a half-life of 53 days. Tritium also decays, with a 12-year half-life, to He^3. None of the beryllium or tritium formed during BBN survives today.



CONSTRUCTING LITHIUM. The heftiest survivor of Big Bang nucleosynthesis is lithium (Li^7). Some stars produce the element, others destroy it. Astronomers study its abundance in the atmospheres of stars in our galaxy's halo to infer its original value. Observations and stellar models suggest these stars contain about half of the lithium available before stars began to shine.

and neutrons — with high accuracy. Using precise measurements of light-element abundances in regions as diverse as stars and intergalactic clouds, astrophysicists now can claim that the density of normal matter in the cosmos is only around 2 percent of the value needed to halt the universe's expansion in the future. Most astronomers and cosmologists believe the universe's total density (the sum of all kinds of matter and energy) exactly equals this critical density.

Because BBN predicts such a tiny fraction for stuff like us, the rest of the universe must be composed of dark matter and dark energy — "dark" in the sense that astronomers don't yet understand what they are. In this way, BBN not only has provided proof that a Big Bang must have occurred, but it also gives us strong evidence that we have much to learn about our universe.

Much has changed from Alpher and Gamow's first calculations 60 years ago to the current era of precision cosmology. Now, a wealth of high-quality data lets scientists test competing cosmological models. But while astronomers have firm reasons for believing in the reality of the Big Bang, they don't need to rely on cutting-edge physics to do so. Big Bang nucleosynthesis shows us that a brief period of well-understood physics has consequences that trickle down 13.7 billion years to the universe we observe.

QUEST for the

New research gives astronomers a broad-brush view of how galaxies evolve. Now, scientists are filling in the details. /// **BY RICHARD S. ELLIS**

THE RING of bright knots in the center of spiral galaxy NGC 1097 is home to a recent burst of star formation, perhaps triggered by tides caused by its small companion galaxy. ESO

STAR FORMATION is so vigorous in the irregular galaxy IC 10, astronomers characterize it as a starburst galaxy. At 1.5 million light-years away, IC 10 is the nearest such system. Researchers want to understand how a modest galaxy like this forms stars so readily. LOCAL GROUP SURVEY/NOAO

MORE THAN 10,000 galaxies inhabit the Hubble Ultra Deep Field, a cosmic snapshot at the very limit of the Hubble Space Telescope's vision. In 2003 and 2004, the telescope repeatedly imaged this 3-arcminute-square patch of sky in the constellation Fornax. The result amounts to a million-second exposure. Distant galaxies look ragged, probably a result of frequent collisions.

NASA/ESA/STScI/STEVEN BECKWITH

first galaxies

Imagine traveling back in time for a firsthand view of history. Astronomers come close to having this ability. Light's finite speed means we can witness distant galaxies as they were when the universe was much younger. Astronomers now have two competing and seemingly incompatible scenarios to explain the origin of galaxies. The only way to determine which theory is right is to look back in time.

Looking back

Astronomers slice the universe into time periods defined by the redshift, a displacement in spectral features to longer wavelengths. These light fingerprints indicate how far we're looking back in time: The larger the redshift, the earlier in history we probe. The ultimate goal for extragalactic astronomers is to identify the first galaxies.

At Caltech, my recent student Dan Stark and I have used gravitational lensing — the magnification of distant galaxies by foreground galaxy clusters — to obtain a glimpse of the earliest galaxies known. What makes this feat possible are powerful cutting-edge tools: the twin 10-meter Keck telescopes in Hawaii and the Hubble and Spitzer space telescopes.

Some of the galaxies we've found lie at redshifts between 8 and 10, corresponding to 500 million years after the Big Bang. At this time, the universe was only 4 percent of its present age.

Galaxies are the universe's most visible components. In the nearby universe, galaxies come in a bewildering variety of sizes, shapes, and luminosities. Astronomers want to know how these differences arose. What physical processes shape a galaxy's destiny?

In the 1920s, Edwin Hubble at California's Mount Wilson Observatory first recognized that the so-called spiral nebulae were not part of the Milky Way, but individual galaxies outside it. Yet serious campaigns to understand how galaxies reached their present form began in earnest only in the 1960s, when many astronomers began to predict theoretically the colors of various nearby galaxies.

Elliptical galaxies contain mainly ancient red stars, whereas spirals and irregulars contain an abundance of young, short-lived, blue stars. Astronomers concluded that elliptical galaxies must have quickly transformed most of their gas into stars at an early stage. By contrast, spirals and irregulars formed stars continuously but at a more moderate pace.

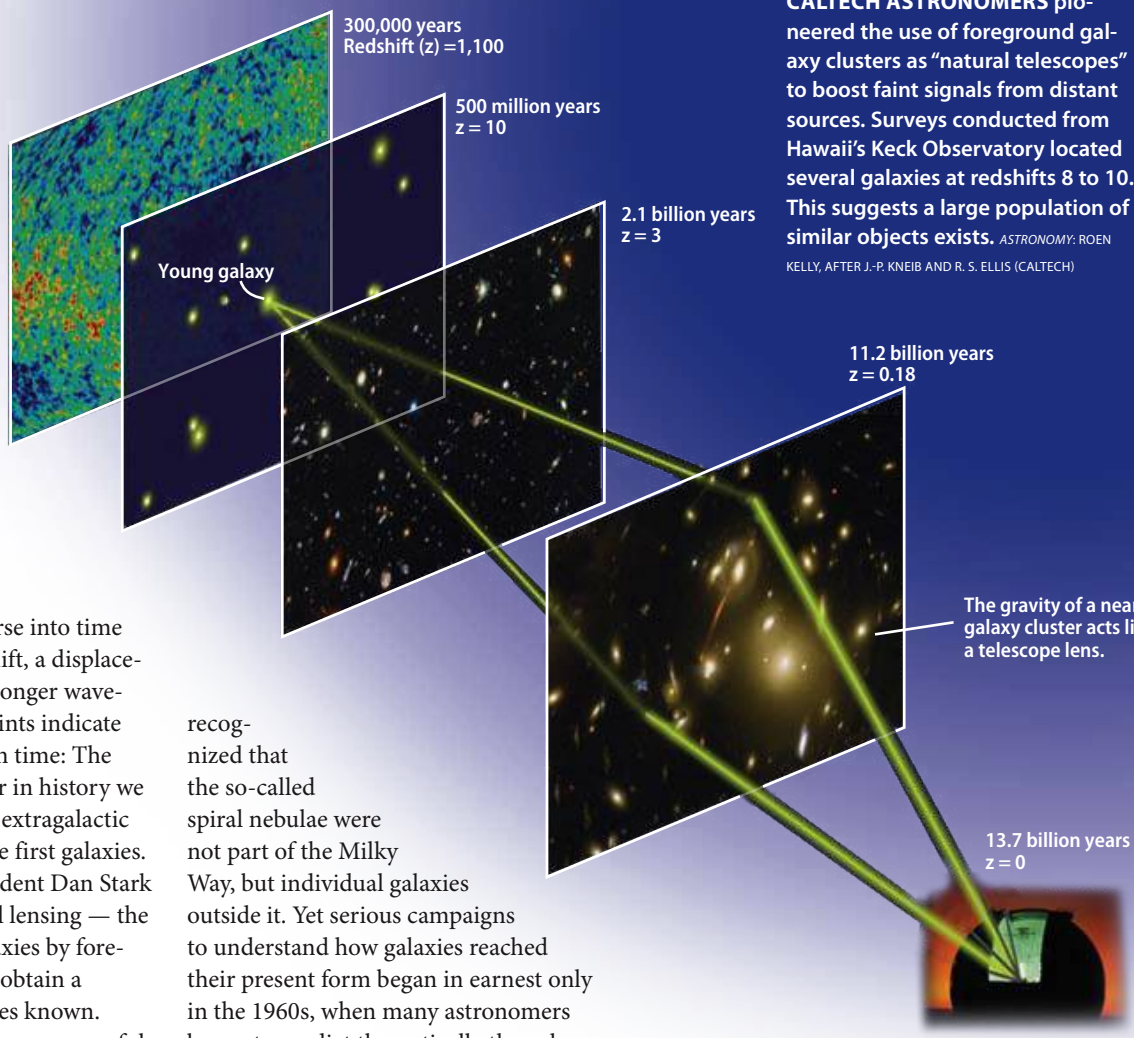
This classical idea for explaining galactic characteristics assumed galaxies were isolated, self-regulated systems. But, relative to their sizes, galaxies now are closer to one another than stars are in the Milky Way. And before the universe reached its current expansion, they were even closer. Therefore, collisions should have occurred frequently.

Moreover, the old theory takes no account of dark matter. In the 1930s, Fritz Zwicky at Caltech discovered dark matter in galaxy clusters, but astronomers didn't prove its presence around individual galaxies until the late 1970s. We now know that most of a galaxy's mass lies outside its visible form in a dark halo. When astronomers incorporated the way gravity congregates dark matter in computer simulations, the influential "cold dark matter" picture of galaxy formation was born.

Dark matter draws together the gas that eventually fuels star formation. What we see as galaxies merely traces dark matter's presence — galaxies are just the icing on the cake. In this view, when gravity brings two dark matter halos together, their respective galaxies and gas clouds collide. The star formation rate increases, consuming and exhausting the gas supply. What's left after all this activity is an elliptical galaxy.

The contrast between the classical view and the dark-matter-dominated model could not be starker. In the former, elliptical galaxies are genuinely ancient systems, perhaps the first to have formed, whereas

How cluster lenses magnify distant galaxies



CALTECH ASTRONOMERS pioneered the use of foreground galaxy clusters as "natural telescopes" to boost faint signals from distant sources. Surveys conducted from Hawaii's Keck Observatory located several galaxies at redshifts 8 to 10. This suggests a large population of similar objects exists. *ASTRONOMY*: ROEN KELLY, AFTER J.-P. KNEIB AND R. S. ELLIS (CALTECH)

Richard S. Ellis, *the Steele Professor of Astronomy at the California Institute of Technology in Pasadena, California, is using the Keck, Hubble, and Spitzer telescopes to probe the nature of the earliest galaxies.*

the dark matter picture sees ellipticals as products of recent mergers. Both may be able to explain the properties of present-day galaxies, but each is based on vastly different evolutionary histories. The only way to determine which is right is to observe what really happened.

New tools

Prior to 1993, astronomers found it difficult to get an accurate census of how distant galaxies differed from their local counterparts. Two powerful observatories changed everything: the Hubble Space Telescope, launched in 1990, and the W. M. Keck Observatory, which commissioned its first 10-meter telescope in 1993.

Fifteen years ago, the most distant normal galaxy astronomers could study lay at a redshift less than 1, which corresponds to a look-back time of some 7 billion years — about halfway back to the Big Bang. With Keck and other ground-based telescopes of comparable power, astronomers now routinely study galaxies to redshift 7, when the universe was less than 1 billion years old.

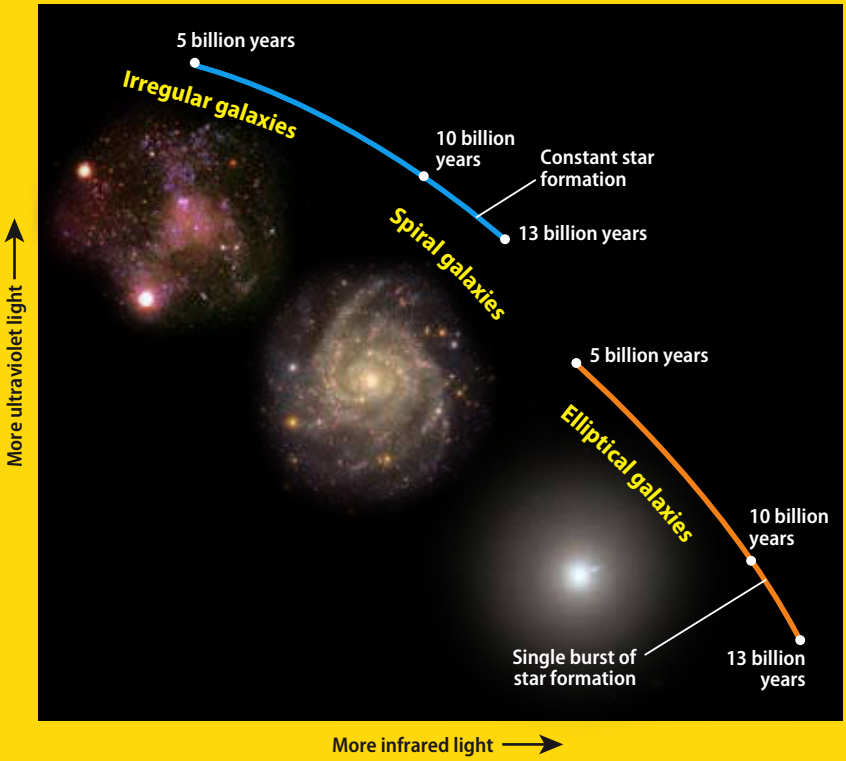
Imagine scanning the crowd in a sports stadium. We easily spot the more exceptional people (say, taller or more colorful). So it is with distant galaxies. Astronomers easily spot the largest or brightest ones, but they can't be sure whether what they're seeing is extraordinary or the norm. So researchers use a variety of techniques to find different galaxy types.

The ability to study distant galaxies at different wavelengths is one of the most important advances in recent times. When

ASTRONOMERS NOW routinely study galaxies to redshift 7, when the universe was less than 1 billion years old.

we look for galaxies at large redshifts using the optical cameras aboard Hubble, we detect star-forming galaxies with an abundance of young blue stars whose ultraviolet signals become redshifted into view. Hubble is then naturally biased to see only those star-forming systems.

Star formation is destiny



ASTRONOMY: ROEN KELLY, AFTER C. STRUCK-MARCELL AND B. M. TINSLEY, 1978; SPIRAL GALAXY: NOAO/AURA/NSF; ELLIPTICAL GALAXY: NASA/ESA/HUBBLE HERITAGE (STScI/AURA)

SPIRAL AND IRREGULAR galaxies emit most of their light in ultraviolet and optical wavelengths, but ellipticals shine brightest in the infrared. A single, ancient burst of star formation naturally explains the colors of most ellipticals. Spirals and irregulars, on the other hand, require continuous star formation to explain their colors.

By contrast, an infrared survey using NASA's Spitzer Space Telescope, launched in 2003, can identify a different population of quiescent galaxies, ones that have stopped forming stars. Combining these approaches gives astronomers a more complete inventory. Ground-based telescopes such as Keck provide the crucial redshifts that place each of these galaxies at its correct time in cosmic history.

Revolution rising

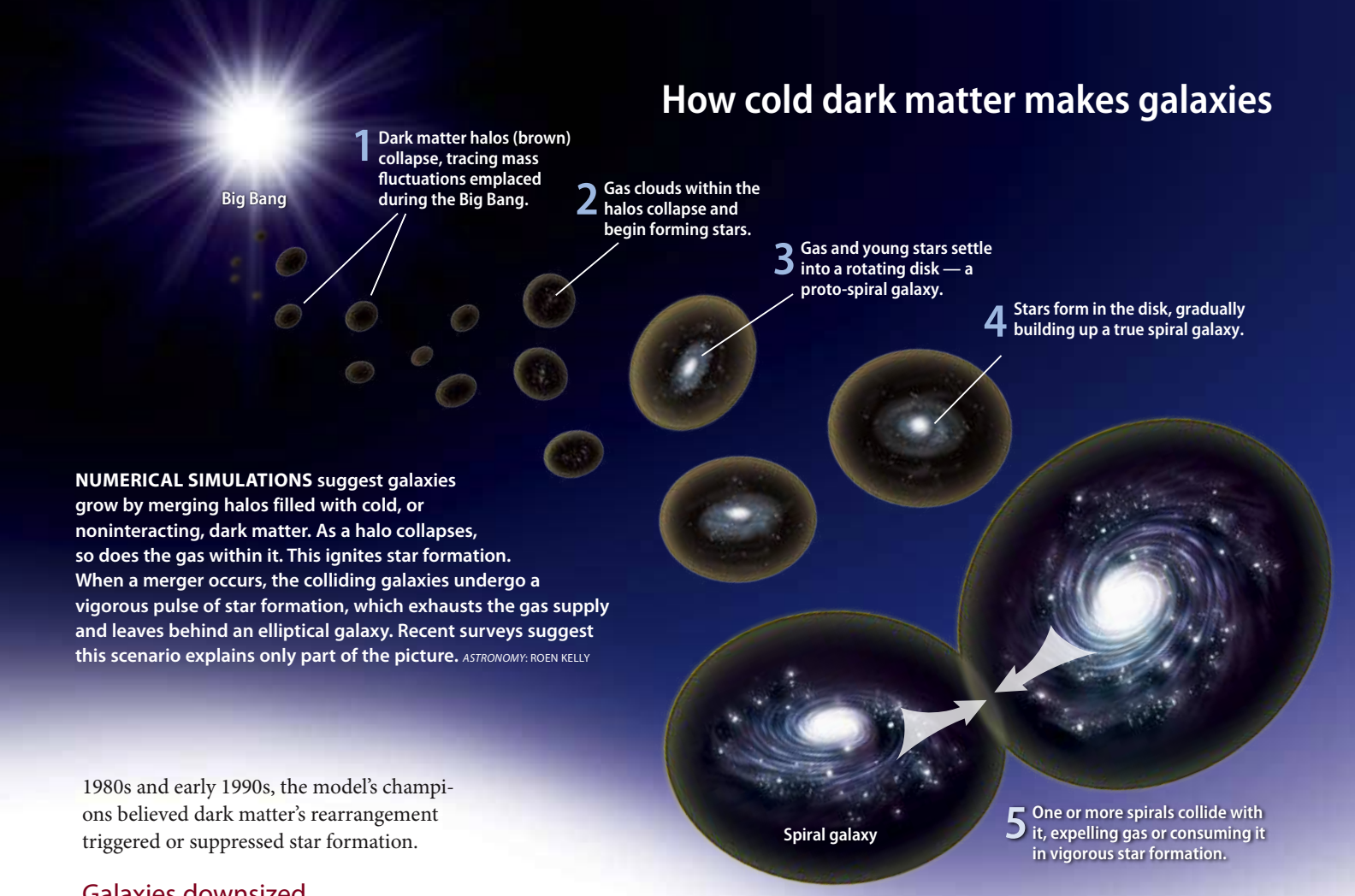
New surveys during the past several years are driving an astronomical revolution. First came the famous Hubble Deep and Ultra Deep Fields, where the Hubble Space Telescope observed a single region of the sky to the limits of its abilities. Then, the wider-area Great Observatories Origins Deep Surveys (GOODS) united imaging and spectra from ground-based scopes with deep observations from Spitzer, Hubble, and the Chandra X-ray Observatory.

Most recently, the Cosmological Evolution Survey (COSMOS) studied an area 10 times larger than the Full Moon. COSMOS included imaging from most major space-borne telescopes and many ground-based observatories, including the European Southern Observatory's Very Large Telescope in Chile, the Keck and Subaru telescopes in Hawaii, and the Very Large Array in New Mexico.

These massive collaborative projects have yielded unique data for millions of faint galaxies. They've also galvanized global collaborations among scientists and created special "selected areas" — sky fields studied by all major telescopes.

One result of this data explosion is improved knowledge of the universe's star formation history. According to Andrew Hopkins of the Anglo-Australian Observatory, who compiled a synthesis of recent results, star formation began at a modest rate early on. It rose to a crescendo between redshifts 2 and 3 and now is in decline.

New research also suggests the dark-matter-dominated scenario for galaxy growth is too simplistic. Yes, dark matter dominates the masses of individual galaxies, and halos can grow through mergers, but the process isn't the primary way a galaxy regulates its star formation. In the


How cold dark matter makes galaxies
Big Bang
1 Dark matter halos (brown) collapse, tracing mass fluctuations emplaced during the Big Bang.
2 Gas clouds within the halos collapse and begin forming stars.
3 Gas and young stars settle into a rotating disk — a proto-spiral galaxy.
4 Stars form in the disk, gradually building up a true spiral galaxy.
Spiral galaxy
5 One or more spirals collide with it, expelling gas or consuming it in vigorous star formation.

NUMERICAL SIMULATIONS suggest galaxies grow by merging halos filled with cold, or noninteracting, dark matter. As a halo collapses, so does the gas within it. This ignites star formation. When a merger occurs, the colliding galaxies undergo a vigorous pulse of star formation, which exhausts the gas supply and leaves behind an elliptical galaxy. Recent surveys suggest this scenario explains only part of the picture. *ASTRONOMY:* ROEN KELLY

1980s and early 1990s, the model's champions believed dark matter's rearrangement triggered or suppressed star formation.

Galaxies downsized

The main challenge to the dark-matter-driven scenario comes chiefly from observations that show many massive galaxies ended their growth and star formation at high redshift, while lower-mass systems continue to add new stars to the present day. This "downsizing," as Len Cowie and his colleagues at the University of Hawaii call it, contradicts a picture in which dark matter halos grow progressively from smaller units into larger ones. Other physical processes must govern how galaxies convert gas into stars. What can they be?

A 2006 survey led by Caltech graduate student Kevin Bundy, now at the University of California at Berkeley, gives us perhaps the clearest view yet of how downsizing occurred over the past 8 billion years. Bundy and his colleagues tracked the distribution of stellar masses in more than 8,000 galaxies with various star formation characteristics out to redshift 1.5. Galaxies appear to form new stars until they reach some critical-mass threshold. After that, star formation ends, and the system matures into a red elliptical. Lower-mass galaxies, which make stars at a much slower rate, never reach the cutoff point.

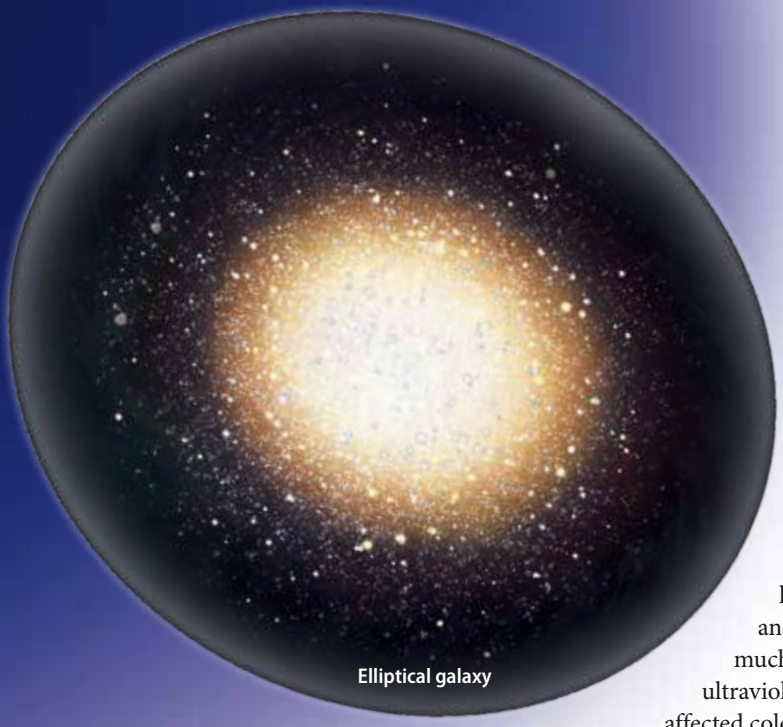
Why do galaxies stop growing? Astronomers are hunting for feedback processes that could inhibit star formation. Perhaps some agent expels gas and shuts down the process. Or maybe gas simply becomes so hot that it can't efficiently cool to collapse into stars. Theorists Darren Croton of the Swinburne University of Technology in Australia and Richard Bower of Durham University in the United Kingdom suspect the cutoff may be linked to the supermassive black holes found in the centers of most galaxies.

In nearby galaxies, astronomers find a close relationship between a galaxy's mass and the size of its black hole: the bigger the galaxy, the more massive the black hole. Black holes can be dormant, as in our Milky Way, or active, as in galaxies with prominent X-ray emission and energetic jets. Several groups now are using X-ray data from Chandra to test the idea that black holes govern star formation in a galaxy. They're attempting to explain downsizing trends by determining which galaxies have active black holes at various times.

When did spirals spiral?

Nearby galaxies show different dynamical properties. Our Milky Way, a spiral galaxy, contains a rotating stellar disk. An elliptical galaxy, on the other hand, is basically a ball of stars, each of which follows a random orbit. To understand a galaxy's internal dynamics, we need detailed spectra from different parts of the galaxy. That's quite a challenge at great distances. A galaxy at redshift 2, for example, has an angular diameter of only 1" to 2". From a typical ground-based observatory, Earth's atmosphere would blur any rotation pattern.

Fortunately, several major telescopes boast another innovation, called adaptive optics, that overcomes this difficulty. With a perfect correction, a 10-meter telescope could attain a resolution of 0.05" at near-infrared wavelengths. This corresponds to details as small as 1,000 light-years for a galaxy at redshift 2! While adaptive optics systems usually don't perform this well in practice, groups led by Reinhard Genzel (Max Planck Institute for Extraterrestrial Physics in Munich) and Chuck Steidel



6 The merger's product is an elliptical galaxy.

(Caltech) have achieved major resolution gains. Their results suggest that many distant galaxies have yet to reach the dynamical maturity we see locally.

Astronomers hope to uncover an evolutionary trend as more teams use the remarkable power of adaptive optics. Among other things, we'd like to know when the rotating disks we see in all present-day spirals became established.

Final frontier

For astronomers interested in galaxy evolution, baby galaxies — those that formed only a few hundred million years after the Big Bang — mark the final frontier. The search for the first galaxies, which astronomers believe formed when the universe was less than 5 percent of its present age, now drives the design of new telescopes.

Some 300,000 years after the Big Bang, hydrogen gas clouds formed. Gravity from dark matter clumps gathered and compressed the clouds, which collapsed and formed the first stars. These pristine systems contained only the nuclei of the simplest atoms, hydrogen and helium, forged in the Big Bang.

Theorists like Tom Abel at Stanford University believe these first stars were short-lived and massive. They shone briefly at redshifts of 20 to 50, long before the wholesale formation of small galaxies at redshifts 10 to 20. This first stellar generation may have been numerous and energetic, so much so that the stars' ultraviolet light escaped and affected cold hydrogen in deep space. This radiation stripped electrons from hydrogen atoms, ionizing them.

Only after this event could visible light traverse intergalactic space. Needless to say, observing when this landmark event occurred, and characterizing the sources responsible for it, excites astronomers.

For galaxies at redshifts beyond 7 — a distance corresponding to 900 million years or less after the Big Bang — cosmic expansion shifts most of their light into infrared wavelengths. This is a particularly challenging region of the spectrum for ground-based observations. Ultimately, future facilities such as NASA's James Webb Space Telescope (JWST) — a 6.5-meter successor to Hubble — will reach much deeper. The observatory, slated for launch in 2014, is optimized for infrared work.

THE FAINT SOURCES found through gravitational lensing are up to 100 times smaller than the Milky Way.

A few years later, if all goes according to plan, a new ground-based observatory called the Thirty Meter Telescope (TMT) will complement JWST. With a mirror 3 times the size of the Keck telescopes and coupled with adaptive optics, TMT will provide details on physically small sources.

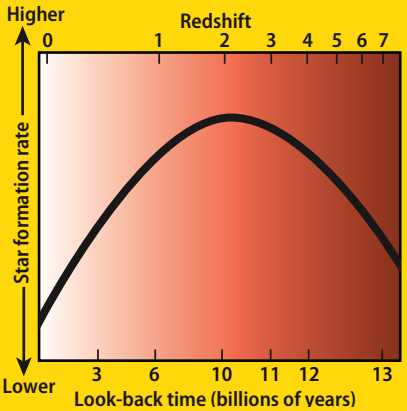
The faint sources Dan Stark and I found using gravitational lensing are, indeed, physically small — only 1,000 light-years across. That's 50 to 100 times smaller than the Milky Way. There seem to be a lot of them, and their collective energy output could represent a significant fraction of the energy needed for cosmic ionization.

We're working now to verify this, but we've almost reached the limits of current astronomical facilities. More detailed studies of the most remote galaxies currently known may simply have to wait for new facilities like JWST and TMT.

Hubble, Spitzer, and Keck enable us to see how galaxies developed from small, immature systems into the majestic forms Edwin Hubble classified in the 1920s. The theory underpinning galaxy growth has made great strides, too, even if the details of how galaxies regulate their star formation remain unclear. We now look to the final frontier, peering back to an era before galaxies formed.

Edwin Hubble understood both our motivations and our challenges. "At the last dim horizon," he said, "we search among ghostly errors of observations for landmarks that are scarcely more substantial. The search will continue. The urge is older than history. It is not satisfied and it will not be oppressed." A

Star formation through time



NEW RESEARCH gives astronomers a census of the universe's star formation history. Activity peaked between 10 and 11 billion years ago. The universe now forms stars at 10 percent of the rate it did 7 billion years ago. *ASTRONOMY:* ROEN KELLY, AFTER A. M. HOPKINS AND J. F. BEACOM, 2006

The secret lives of black holes

A black hole's spin may power gamma-ray bursts and galactic jets. But its rotation has been hard to measure — until now.

/// **BY STEVE NADIS**

A black hole's extreme gravity takes us to the very limits of physics — and about as far from everyday experience as we can get. At its central singularity, density and curvature race toward infinity, space and time come undone, and the tools of conventional physics are useless.

Yet, in an irony worthy of its subject, black holes boil down to something rather simple. As the late University of Texas physicist John Wheeler famously said, "Black holes have no hair" — that is, no details. The only quantities an outside observer can glean about a black hole are its mass and spin. The complex history of the stuff that made its way inside the black hole — as a dying star or a shredded galaxy — is simply radiated away.

"That's the miracle of a black hole," explains Ramesh Narayan of the Harvard-Smithsonian Center for Astrophysics (CfA) in Cambridge, Massachusetts. "If you can measure its mass and spin, you have, in a sense, obtained the complete story."

Steve Nadis, *a frequent* Astronomy *contributor, keeps tabs on advances in astrophysics from his home in Cambridge, Massachusetts.*

DOES A BLACK HOLE'S ABILITY to launch powerful jets arise from its surrounding gas disk? Or do these events somehow extract energy from the spinning black hole, which acts like a giant flywheel? Theorists have debated these questions for 30 years, but understanding what's happening requires measurements astronomers only now are able to make. BLACK HOLE ILLUSTRATIONS: *ASTRONOMY:* ROEN KELLY

While spin is an essential piece of data for understanding black holes themselves, it's also crucial for understanding how black holes influence their environments. Now, astronomers have found ways to measure a black hole's spin.

Two numbers

Although a black hole appears simple from a distance, it undergoes complex interactions with the hot gases swirling around it. This is especially true for a rapidly rotating black hole. By virtue of its powerful gravitational field, the spinning hole literally drags space-time along with it. So, any inquiry into how black holes interact, says CfA astronomer Jeffrey McClintock, must begin with mass and spin.

For stellar-sized black holes in X-ray binary systems, mass calculations are reasonably straightforward. Astronomers record how fast the companion star circles around the black hole, and, from this, they infer its mass. In fact, mass estimates now exist for more than 20 stellar-mass black holes.

Unfortunately, this technique doesn't work for supermassive black holes, which range from a million to a billion suns. It's usually impossible to see stars moving around another galaxy's center, so scientists may never accurately know the mass of its black hole behemoth.

Until recently, measuring a black hole's spin was beyond astronomers' grasp. Scientists quantify a black hole's rotation using a dimensionless parameter called a* (pronounced "a-star"). It ranges from 0 — for a nonspinning, so-called Schwarzschild-type black hole — to 1, an object spinning as fast as general relativity will allow.

Three techniques for determining a* now are on the table. Astronomers have a fourth ready to implement, but they'll need a new space observatory to do so. It's an exciting time for black hole researchers.

Fit the continuum

McClintock and Narayan are pioneering an approach called continuum fitting. It involves equal parts of theory and observation. They study X-ray binary systems, where a companion star reveals the presence of a stellar-mass black hole. This lets them get a good fix on the black hole's mass — the starting point for their analysis.

The black hole's intense gravity strips gas from the neighboring star. The gas spirals toward the hole and surrounds the invisible object in an accretion disk of hot plasma. Temperatures approaching 20 million kelvins occur on the disk's inner edge, where the gas moves the fastest.

This hot material radiates X rays until the gas reaches its innermost stable circular orbit (ISCO). After that, the gas plunges toward the hole so rapidly that it gives off no significant radiation.

McClintock and Narayan analyze the overall continuum spectrum of X-ray emissions, ignoring individual spectral lines, to gauge the gas temperature. From this, they can deduce the hole's ISCO because the closer a clump of gas gets to the hole, the greater the hole's gravity affects it. This makes the gas orbit faster and heat up due to friction. But a hole's ISCO radius varies with its spin, according to the precepts of general relativity.

One object spins more than 950 times per second — within 2 percent of the maximum value.

By knowing the radius, astronomers can determine how fast the black hole spins. A nonrotating, 10-solar-mass black hole has an ISCO of 56 miles (90 kilometers). If the same black hole instead were spinning at the maximum rate (a* equals 1), its ISCO would shrink to 9 miles (15 km).

Using data collected by NASA's Rossi X-ray Timing Explorer (RXTE) satellite, McClintock, Narayan, and four colleagues determined spins for three black holes. Shane Davis, then at the University of California at Santa Barbara, measured a fourth.

One object — GRS 1915+105 — stands out from the crowd with its ultrafast rotation. It spins more than 950 times per second, more than 98 percent of the maximum value relativity allows.

University of Maryland astrophysicist Chris Reynolds declares that the basic reasoning is sound, but he's less confident about the details. He wonders, "Do we understand the spectrum well enough to say the spin rate is 0.98 rather than 0.95?"

Iron lines

McClintock and Narayan disregard individual lines within a binary's X-ray spectrum, but other astronomers focus on one of the best-studied spectral features — the iron emission line. This feature blurs near a black hole due to an effect called gravitational redshift. As gas closes on the black hole, time runs slower.

"An emitting atom is like a clock," Reynolds explains. "The frequency of emission gets lower and lower as you approach the black hole." By analyzing this spectral line, he and other investigators can determine the extent of gravitational redshifting and surmise how close to the black hole the accretion disk extends. As with continuum-fitting, the iron line tells astronomers the ISCO's radius, which, in turn, tells scientists the hole's spin.

So far, astronomers have applied the technique to a 10-million-solar-mass black hole in the center of the spiral galaxy MCG-6-30-15. The result was an a* measurement of 0.987. In other words, this object appears to be spinning at 98.7 percent of its theoretical limit. Before Reynolds starts trumpeting that number, however, he wants to make absolutely sure he's really seeing the ISCO.

Song of the black hole

Other astronomers are taking advantage of the fact that some stellar-mass black holes "sing" at least part of the time. They emit high-frequency notes known as quasi-periodic oscillations.

The oscillation frequency tells researchers how hot the X-ray-emitting gas orbiting the black hole is. This, in turn, reveals the orbital radius of the gas. If that radius turns out to be smaller than the ISCO of a nonrotating black hole, they conclude the object is spinning.

But there's a problem. Says Ron Remillard at the Massachusetts Institute of Technology (MIT) in Cambridge, "We still can't convert these oscillations into actual spin numbers." There are several models for the oscillations, and each one yields a different spin.

Black hole anatomy

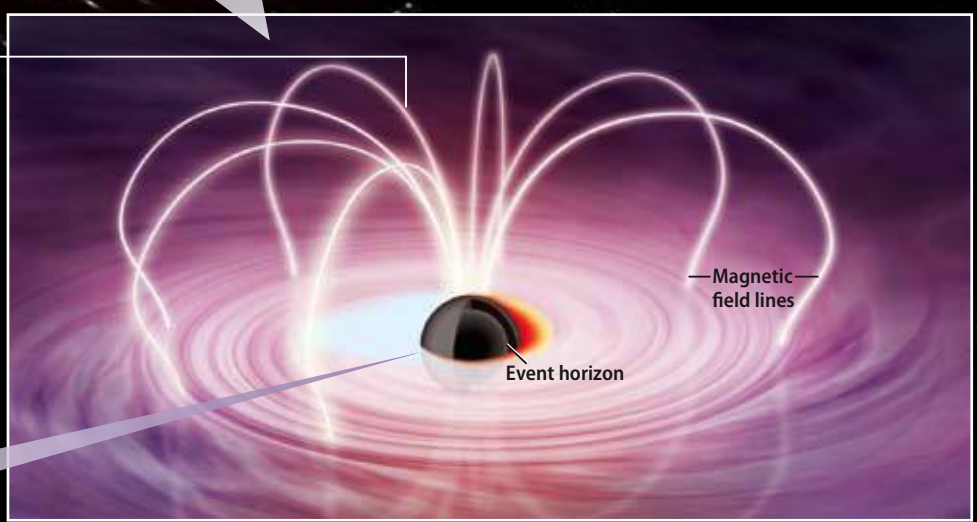
GRAVITATIONAL LENSING
Light from objects behind the black hole is reddened and distorted by the hole's gravity.

DOPPLER SHIFT
At left, radiation from gas spinning rapidly toward the observer shifts to higher energy (blueshifted). Gas at right rotates away from the observer, and its emission is redshifted.

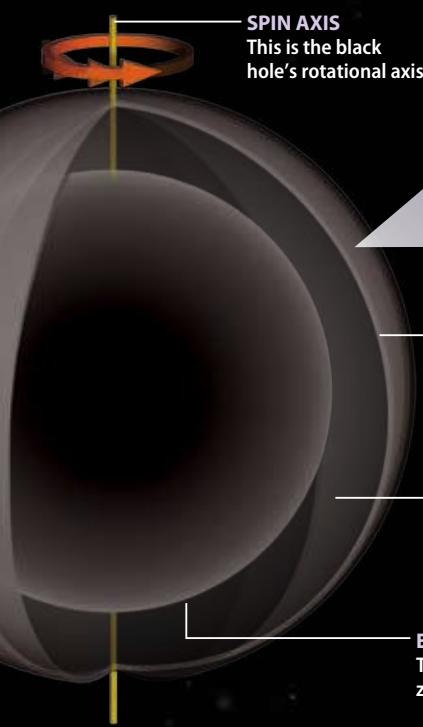
INNER ACCRETION DISK
Matter falling toward the black hole collects in a disk that surrounds it. Friction heats the gas.

GRAVITATIONAL REDSHIFT
Radiation emission from gas in front of the black hole also is redshifted, in part because photons lose energy traveling out of the black hole's gravitational field.

DISK MAGNETIC FIELD
The disk's magnetic field becomes amplified and forms a corona near the hole. Magnetic field lines can extract energy from the black hole. This could either accelerate a jet of matter or, as shown here, enhance the disk's X-ray emission.



SPIN AXIS
This is the black hole's rotational axis.



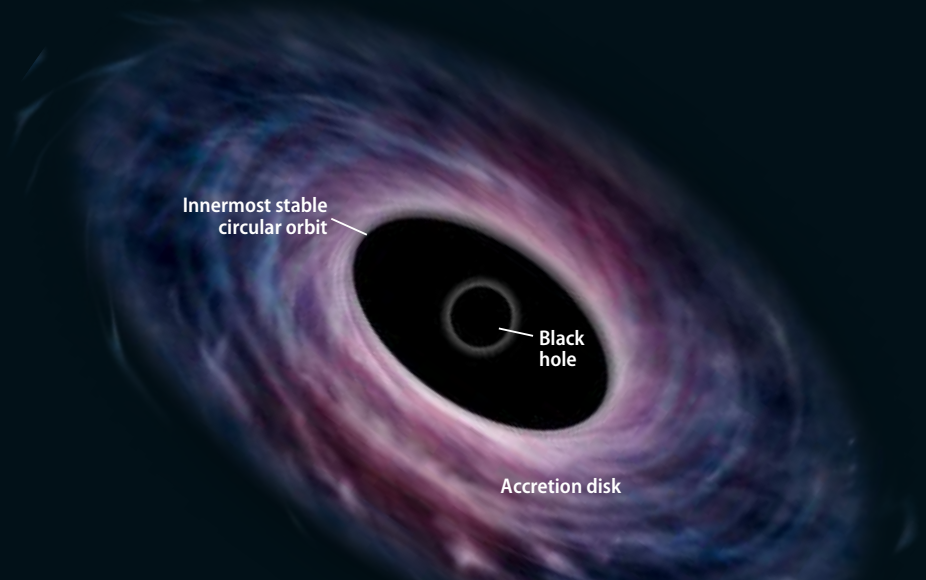
STATIC LIMIT
Inside this boundary, nothing can remain stationary, even if it moves at light-speed, because the spinning black hole's gravity drags space-time along with it.

ERGOSPHERE
Between the event horizon and the static limit, in a region called the ergosphere, all trajectories must rotate in the same direction as the black hole.

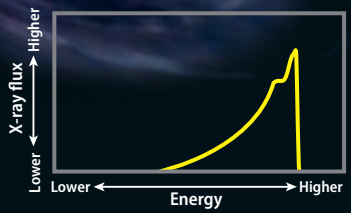
EVENT HORIZON
This is the surface of no return — it marks the zone from which no matter can escape.

MOST OF A BLACK HOLE'S rotational energy resides in the ergosphere, a region where any object must rotate in the same direction the hole spins. Its actual size in the sky would be less than 1 millionth of an arc-second — comparable to newsprint placed on the Moon. Space-based X-ray interferometers could achieve such resolution.

Nonspinning black hole

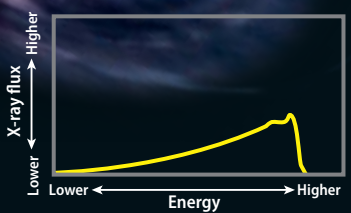


ASTRONOMERS USING NASA'S Chandra X-ray Observatory and the European Space Agency's (ESA) XMM-Newton satellite studied iron emission in the hot gas of a black hole's inner accretion disk. Atoms closest to the black hole emit radiation at lower energy, which produces a strongly skewed signal.



Spinning black hole

A PARTICLE'S ORBIT near a black hole depends on how the hole warps space-time, which, in turn, also depends on how fast the black hole spins. A spinning black hole drags space around with it and allows atoms to approach closer than is possible for a nonspinning black hole. The tighter orbit produces stronger gravitational effects, which means more of the X rays from iron atoms shift to lower energies.



The approach still has great promise, Remillard says, "because these frequency measurements are good to 10 percent." What's more, the oscillations seem to come in pairs of frequencies that have a 3-2 ratio (such as 450 and 300 hertz). Those frequencies don't change over time, even if the black hole goes silent for a year or more before singing again.

Given the possibilities for a crisp, clear measurement, says McClintock, "This might prove to be the best way to get the spin, once we have a model that tells us exactly what's oscillating."

Turning to polarization

A fourth proposed strategy aims to exploit the expected polarization of X rays emitted from accreting black hole systems. Both the curvature of space-time near the hole and the twist caused by the black hole's rotation could lend a preferred orientation to the electromagnetic waves. In principle, notes Reynolds, "The black hole spin could show up in the polarization signal, assuming you know the polarization of the initial source, which is far from clear."

"This is unexplored discovery space," says Jean Swank of NASA's Goddard Space Flight Center in Greenbelt, Maryland. "These X-ray photons are carrying additional information that has never been studied."

The biggest problem with the technique is that it needs to be done from space, and no space mission designed to measure polarized black hole X rays is even being planned. NASA scientists hope to install a polarization detector on the proposed International X-ray Observatory, a joint American, European, and Japanese next-generation X-ray mission. But the future of this project itself remains uncertain.

"We'd like to have all four techniques established," McClintock says, because the spin calculation is complex. Many assumptions go into each calculation, and uncertainties creep in at various stages. "But once you get the same answer from more than one technique, you know you're there," he says.

Memento

Astronomers aren't just interested in spin for spin's sake. They're convinced spin holds the key to solving many long-standing puzzles. It can tell us, for instance, how black holes are born and how they grow.

"The spin retains a memory of these things," Reynolds says. Such measurements

also can help investigators test ideas about how phenomena like astrophysical jets and gamma-ray bursts work.

Just what drives the violent jets emanating from black holes has been a mystery for at least 30 years. "The question, long debated, is whether the power behind jets and other phenomena derives from the black hole or from the accretion disk," explains Roger Blandford, an astrophysicist at Stanford University who has studied the problem since the 1970s. While others disagree, Blandford thinks the source is the black hole's rotation. The spinning hole acts like a "giant flywheel, with some of its energy there for the taking," he says.

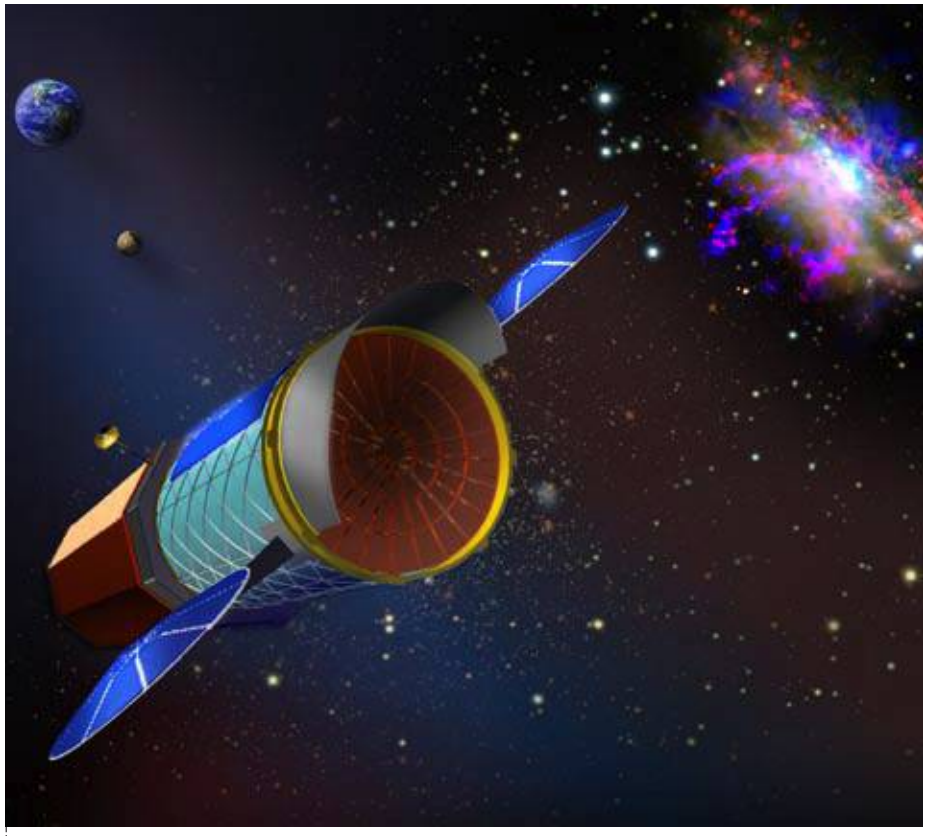
That seems plausible to McClintock. "Maybe jets are driven by the enormous spin of these black holes," he says, "but unless you have spin measurements, you can't test the theory." That's why he's intent on acquiring at least a dozen solid measurements. GRS 1915+105 offers an intriguing example: Its famous jets whisk matter through space at roughly 92 percent of light-speed, and its estimated spin approaches the theoretical limit.

"You'd really like to have spin measurements for a large number of jet-producing black holes," says David L. Meier at the Jet Propulsion Laboratory in Pasadena, California. "You'd look at all these black holes spinning at different rates, look at the distribution of jet power, and try to find a pattern." The good news, says Meier, is that we may soon be in a position to do it.

Jets and GRBs

Gamma-ray bursts (GRBs) have posed a similar challenge to theorists since satellites first detected them in 1969. Today's leading theories hold that one type of GRB occurs when the cores of massive stars collapse into fast-spinning black holes.

Until recent measurements of objects like GRS 1915 or MCG-6-30-15, says CfA's Narayan, "We didn't know for sure that such objects existed. Based on the few data points gathered so far, it appears that rapidly spinning black holes are pretty common."



THE PROPOSED International X-ray Observatory would use at least six instruments working in unison. The resulting measurements would have 100 times the sensitivity of NASA's Chandra X-ray Observatory or ESA's XMM-Newton, both currently in orbit. NASA

Stan Woosley, an astrophysicist at the University of California at Santa Cruz, agrees. "We always thought massive stars must be rotating rapidly when they collapse, but for a long time all we've had is guesses." In some models, evolved stellar cores often don't rotate fast enough to power GRB jets. "It's nice to finally have some measurements to work with," he says.

> If Einstein is wrong, detailed data about spinning black holes offer scientists a way to find out.

Once astronomers have amassed many credible spin measurements, they may be able to test general relativity as it's never been tested before — within the universe's strongest gravitational fields.

"If there's a big surprise out there, if Einstein is wrong, one way to find out is by pushing these spin measurements," Reynolds says. Astronomers say the proposed International X-ray Observatory offers the resolution needed to put relativity through such a test.

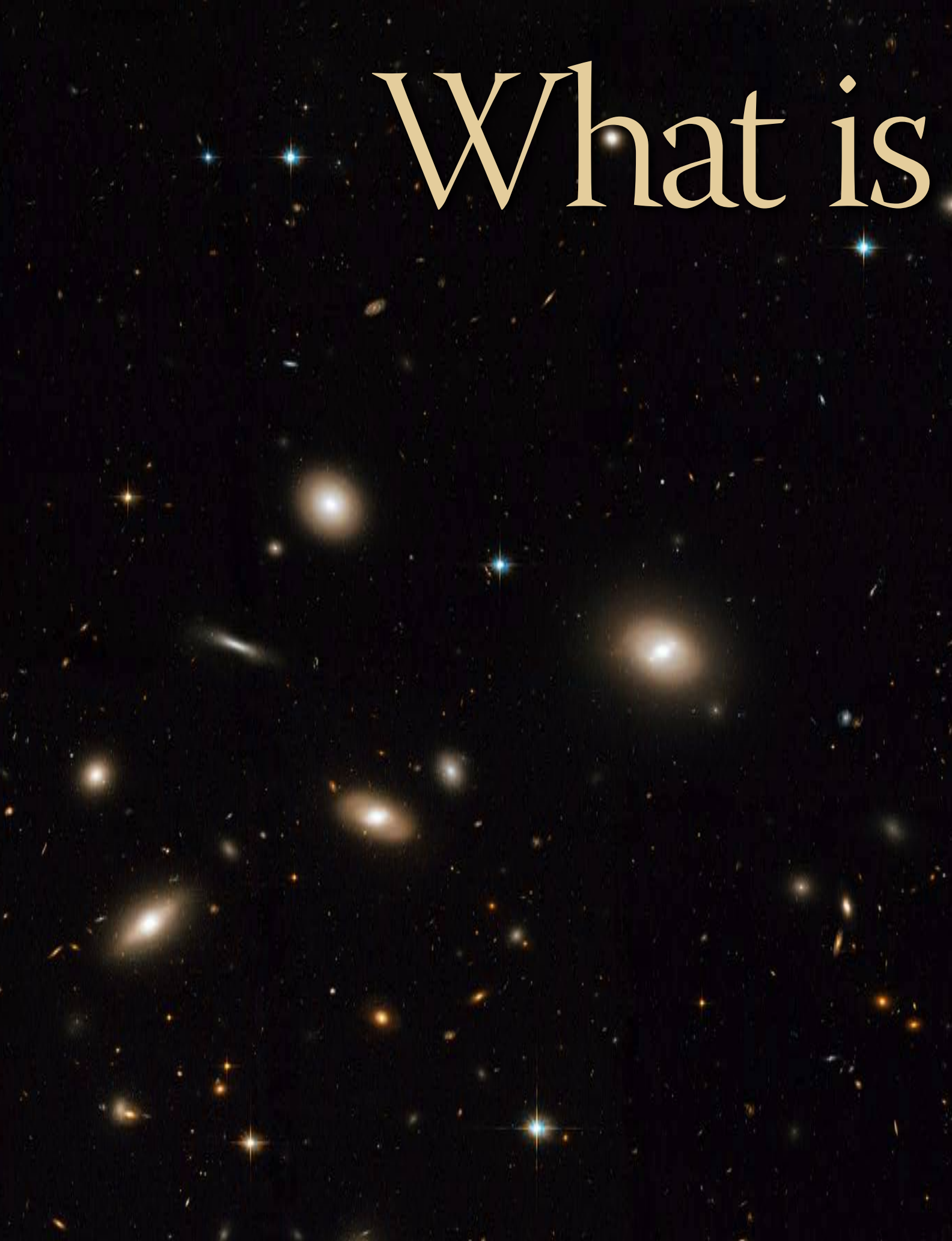
At the same time, precise spin measurements also might lend support to the "no hair" theorem itself. If multiple approaches yield the same answers, Narayan explains, it would validate the notion that mass and spin tell astronomers everything about a given black hole.

That's a remarkable idea. "Consider anything else you might try to describe in nature, such as a simple grain of salt," McClintock suggests. "It would take trillions of numbers to specify the position of all the atoms and all the atomic states."

Or imagine a distant view of Earth. From far off, the only thing you can detect, the only thing that matters, is the planet's mass. "But as you get closer, you see oceans, mountains, trees, and people," Narayan says. You'd need a long list of numbers to describe it all.

Black holes are different. We can never see them directly. Instead, they make themselves known indirectly, through effects related to their intense gravity and rapid rotation. Together, mass and spin bring scientists closer to a black hole's abyss.

What is



dark energy?

A mysterious force accelerates cosmic expansion and pervades all of space.

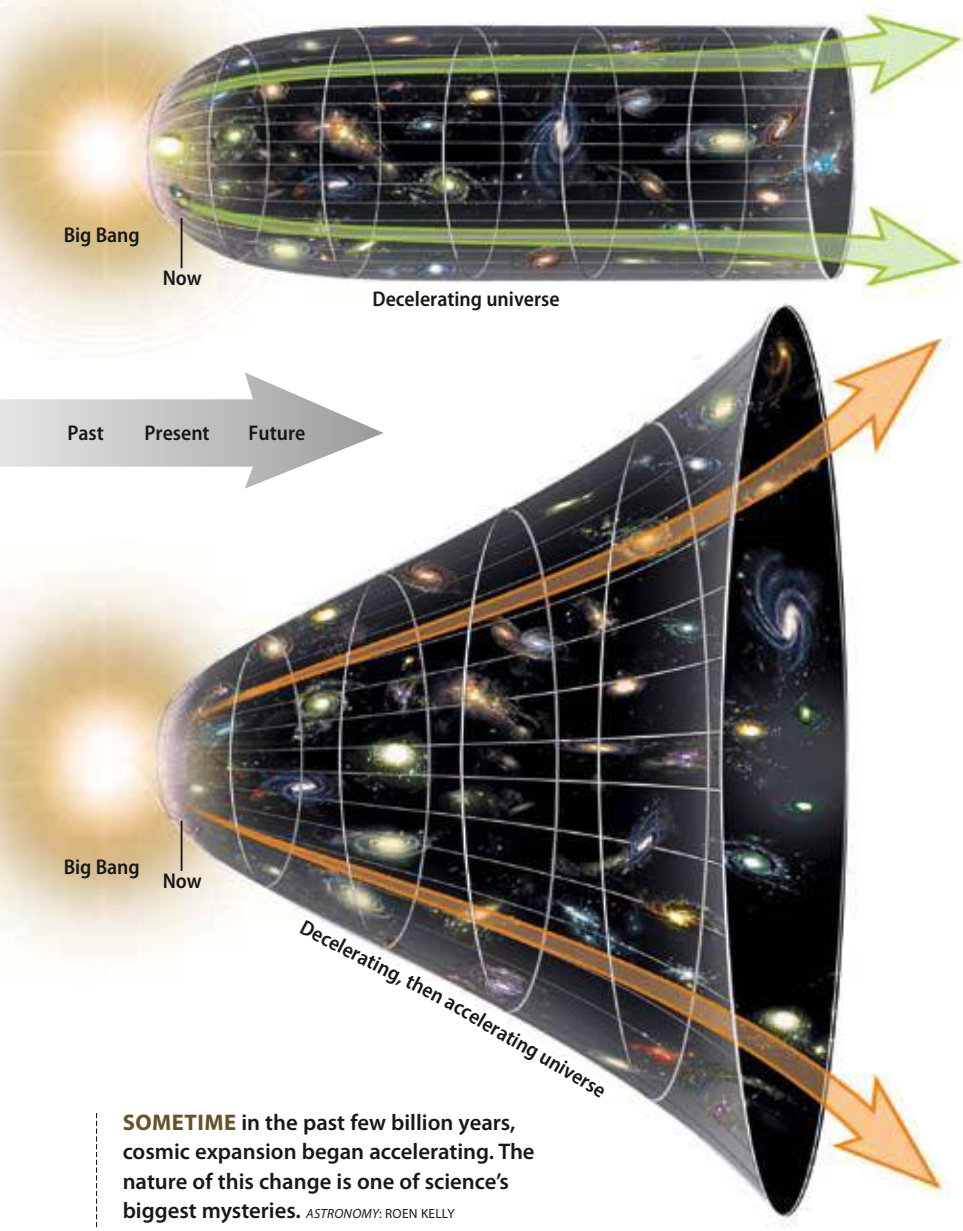
/// BY STEVE NADIS

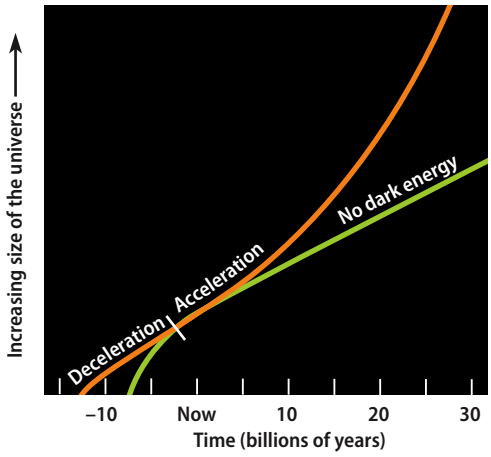
Most astronomers now subscribe to a startling proposition: Nearly three-quarters of the universe comprises a strange entity that's spread evenly throughout space — it may even be a part of space itself. This mysterious entity, which astronomers call "dark energy," causes our universe's expansion to speed up. If dark energy remains as persistent as it appears, it will disperse everything in the cosmos into a cold, ever-expanding void.

This strange scenario has gained credence since 1998, when studies of distant type Ia supernovae suggested these stellar explosions, which are

THE COMA GALAXY CLUSTER is a dense collection of galaxies, with thousands of them spanning some 20 million light-years. The strong gravitational interactions between the galaxies and the as-yet-unidentified material called dark matter holds the cluster together. Dark energy, the strange force that's pushing the universe apart, can't pull apart such clusters. NASA/ESA/THE HUBBLE HERITAGE TEAM (STScI/AURA)

A cosmological turning point





SOMETIME in the past few billion years, cosmic expansion began accelerating. The nature of this change is one of science's biggest mysteries. *ASTRONOMY*: ROEN KELLY

UNTIL 1998, cosmologists thought the universe was slowly decelerating as the gravity of all matter within it slowed expansion. Since then, astronomers have accumulated evidence that the expansion began accelerating as dark energy counters gravity's tug. The most recent data indicate cosmic acceleration will continue forever. *ASTRONOMY*: ROEN KELLY

known for uniform energy output, were dimmer — and thus farther away — than expected for their redshifts. Astronomers proposed that an unseen force was causing the universe to expand at an accelerated rate. Cosmic microwave background (CMB) measurements from the Wilkinson Microwave Anisotropy Probe (WMAP) and other experiments supported this notion.

"There was a moment of disbelief," acknowledges Saul Perlmutter of the Lawrence Berkeley National Laboratory, who leads one of the supernova-study teams. But as data filtered in from multiple fronts, astronomers moved from denial to grudging acceptance. Dark energy, which many consider to be the deepest, most important mystery in all of science, was here to stay.

"Dark energy is not predicted by the physics we understand," says Adam Riess of the Space Telescope Science Institute in Baltimore. "So, learning about it will almost certainly lead us to something new and exotic."

Groping in the dark

Astronomers have three leading explanations for dark energy, and deciding among them will be a major focus of cosmologists for years. The first is the cosmological constant, proposed (and later recanted) by Albert Einstein. In this view, dark energy is an intrinsic, uniform property of space. The second idea, called quintessence, involves an unidentified energy field of varying strength that fills space like a fog. Scientists envision this unidentified energy as similar to that which drove inflation, the rapid burst of expansion in the instant following the Big Bang.

The third alternative? Dark energy is an illusion. Instead, the effects we see result from a breakdown in Einstein's theory of gravity over the largest distance scales. Most scientists have focused on the existence of dark energy. But this "modified gravity" alternative deserves serious consideration, as well, says Princeton University's David Spergel. The right explanation may turn out to be "none of the above."

While these competing ideas differ dramatically, says Daniel Eisenstein of the University of Arizona, "From an observational standpoint, the differences could be extremely subtle. You can construct all kinds of models that give you answers that are close to the cosmological constant. The only way to tell the difference is by doing the measurements extremely accurately."

It won't be easy, Perlmutter admits. "It took us 10 years to realize the universe is accelerating, and it will take at least as long to figure out what's behind it," he says. "The good news is that we have ways of attacking the problem."

"We need to throw everything we can at this problem," insists Robert Nichol of the University of Portsmouth, England. "We

Steve Nadis, *a frequent* Astronomy *contributor, often writes about cosmic conundrums.*

need to throw the kitchen sink at it." All told, astronomers are pursuing roughly a dozen different approaches. So far, the big payoff has come from supernovae, which provided the first direct measure of cosmic acceleration and are scientist's favorite tools.

Standard candles

To chart the universe's expansion history, astronomers measure a supernova's luminosity and redshift. Because each type Ia supernova releases about the same energy, each blast's brightness reflects its distance from Earth. The redshift tells us how much the light has stretched (how much the universe has expanded) during its travel. By looking at supernovae over a broad redshift range, astronomers discovered that the universe's expansion rate has varied.

The focus now, says Riess, is to push back to higher redshifts in order to measure the acceleration's onset. The Hubble Space Telescope is the best tool for finding distant supernovae. But a dedicated space instrument, such as the proposed Supernova/Acceleration Probe (SNAP), would hasten the process. As now envisioned, SNAP would best Hubble with both a larger field of view (0.7°) and a billion-pixel imager.

When did dark energy's push overtake gravity's pull? Based on Hubble observations, Riess believes the balance tipped about 5 billion years ago, but he'd like to know exactly when the changeover occurred because predictions differ among theories. The transition occurs earlier in quintessence models, for instance, than in cosmological-constant ones.

> "IT TOOK US 10 YEARS to realize the universe is accelerating, and it will take at least as long to figure out what's behind it." — *Saul Perlmutter*

Surveys now in progress will amass bigger and more homogeneous data sets. The ESSENCE program at the Cerro Tololo Inter-American Observatory in Chile has almost completed a 5-year project to measure 200 supernovae at intermediate redshifts. Another 5-year effort, the Supernova Legacy Survey at the Canada-France-Hawaii Telescope on Mauna Kea in Hawaii, is designed to detect and monitor several hundred high-redshift supernovae. "It's hard to say how big a sample we need," notes Riess. "It depends on what nature has in store for us."

Meanwhile, astronomers need to understand type Ia supernovae better to make them truly reliable dark-energy probes. "There weren't as many heavy metals in the early universe, which could lead to a difference in explosion physics — and, hence, brightness — that might fool us," explains Harvard University physicist Christopher Stubbs. Astronomers are trying to address this concern through close scrutiny of supernova spectra.

Wiggling baryons

One method for exploring dark energy potentially has the highest precision, according to University of Oklahoma cosmologist Yun Wang. It involves "baryonic acoustic oscillations" — fluctuations in the distribution of photons and particles of ordinary matter (baryons) caused by sound waves sloshing around in the early universe. Think of these fluctuations as the ripples made by tossing a pebble in a glass-smooth pond. The waves left a faint imprint in the distribution of galaxies. The galaxies, in other words, tend to space themselves on a distinct physical scale. They constitute a "standard ruler," just as type Ia supernovae serve as standard candles.

The basic approach is to find a large number of galaxies with the same redshift. Knowing that the ruler's length correlates with redshift, observers then determine the scale of peak clumpiness. By measuring the angle this "preferred length" subtends, scientists say they can determine the distance to the galaxy. The distance-redshift relation, as with supernovae, tells researchers how dark energy has influenced the universe's expansion.

Daniel Eisenstein and colleagues first measured these baryon wiggles in 2005 in Sloan Digital Sky Survey data. The result validates the supernova findings through different means, but it will take a more precise redshift survey, drawing on more galaxies in a larger volume of space, to probe dark energy further. "With Sloan, we detected the effect with 4 percent precision, but we'd like to get to 1 percent precision," Eisenstein says.

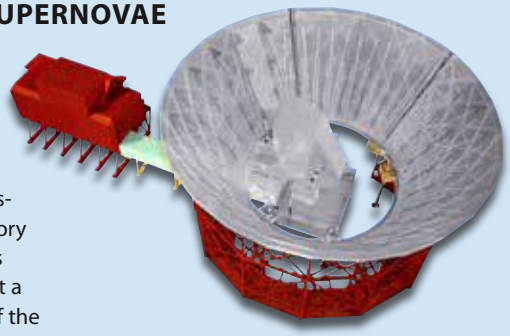
DESPERATELY SEEKING SUPERNOVAE

The most far-flung supernovae are extremely faint and detectable only in wavelengths blocked by Earth's atmosphere. NASA and the U.S. Department of Energy are sponsoring the Joint Dark Energy Mission (JDEM), a space-borne observatory dedicated to unlocking dark energy's secrets. JDEM, to be launched at least a decade from now, will employ one of the following designs:

• Dark Energy Space Telescope (DESTINY). This project, headed by Tod Lauer of the National Optical Astronomy Observatory, is a 1.8-meter near-infrared space telescope dedicated to surveying high-redshift supernovae.

• Advanced Dark Energy Physics Telescope (ADEPT). This 1.3-meter space telescope would monitor 1,000 type Ia supernovae, capture redshifts for more than 100 million galaxies, and study baryonic acoustic oscillations. Charles Bennett of Johns Hopkins University heads up ADEPT.

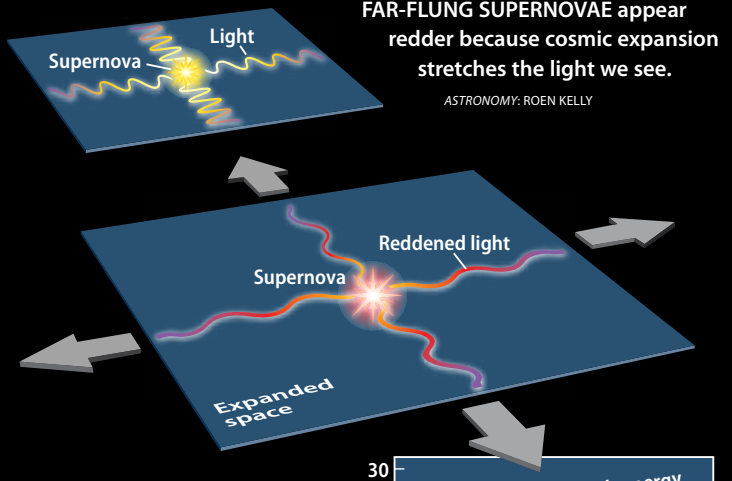
• Supernova/Acceleration Probe (SNAP). This 2-meter optical and near-infrared scope would discover and measure the spectra of 6,000 distant supernovae during its 3-year mission. It would also perform a weak-lensing survey. Saul Perlmutter of the Lawrence Berkeley Laboratory is the principal investigator. — *S. N.*



THE SOUTH POLE TELESCOPE (SPT) observes the sky at millimeter and longer wavelengths, a region between radio and the infrared. Its first key project, a wide-area survey of galaxy clusters using the Sunyaev-Zeldovich effect, complements supernova studies. UNIVERSITY OF CHICAGO

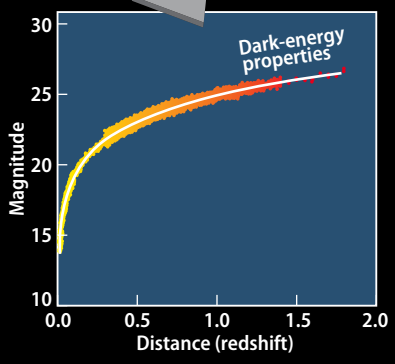
Four ways to target dark energy

High-redshift supernovae



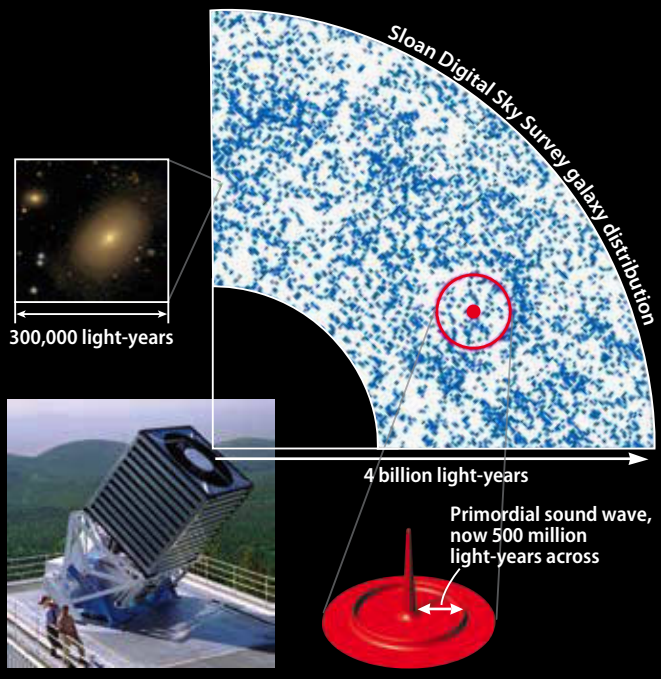
FAR-FLUNG SUPERNOVAE appear redder because cosmic expansion stretches the light we see.

ASTRONOMY: ROEN KELLY



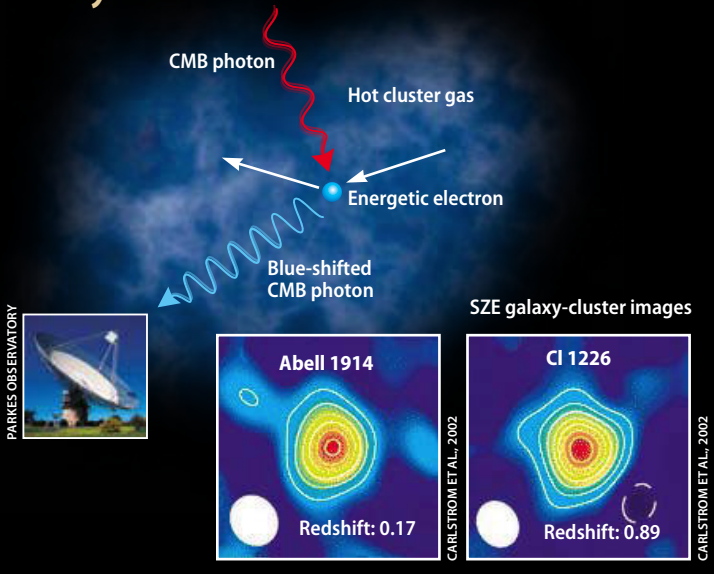
THE MOST DISTANT type Ia supernovae look dimmer than they should, which indicates they're located farther from us than expected from the standard energy of these blasts. SN 1997ff, which lies at redshift 1.7, is the farthest such supernova known, but most of the type Ia variety have redshifts less than 1. In a single year, a space telescope dedicated to finding supernovae could identify thousands at redshift 1.5 and beyond. This would reveal much about dark energy's properties. *ASTRONOMY:* ROEN KELLY

Baryonic acoustic oscillations


Sloan Digital Sky Survey galaxy distribution
300,000 light-years
4 billion light-years
Primordial sound wave, now 500 million light-years across

SOUND WAVES in the early universe left their imprint in the cosmic microwave background (CMB). In 2005, Daniel Eisenstein and colleagues announced the discovery of corresponding ripples in the distribution of galaxies mapped as part of the Sloan Digital Sky Survey (SDSS). Because the ripples appear both in relatively nearby galaxy groups and the high-redshift CMB, they offer a geometric measure of the relative distance between these widely separated redshifts — and more clues to cosmic acceleration. SDSS

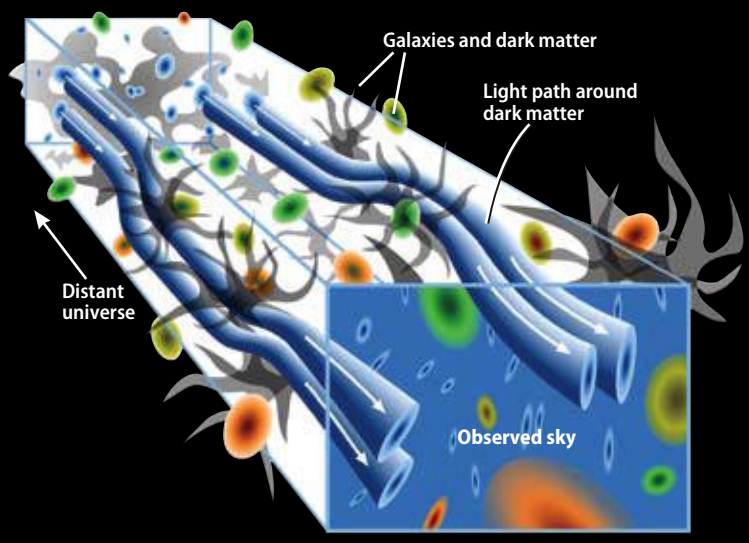
Sunyaev-Zeldovich effect



HOT GAS in massive galaxy clusters distorts the CMB. The gas' fast-moving electrons can give a CMB photon an energy boost. This distortion of the CMB is called the Sunyaev-Zeldovich effect (SZE).

ASTRONOMY: ROEN KELLY

Weak lensing



LIGHT FROM the distant universe wends its way through gravitational distortions caused by regions of dark matter. This creates a slight shear in individual galaxy images — so slight, it's apparent only when astronomers compare large numbers of galaxies. LSST CORPORATION

Two experiments are planned to achieve this goal. The Hobby-Eberly Telescope Dark Energy Experiment will survey a million galaxies out to redshift 3, starting in 2010. For comparison, this is almost double the 1.7 redshift of SN 1997ff, the most distant supernova known. Eisenstein is working with a competing group that hopes to install a Wide-Field Multi-Object Spectrograph (WFMOS) on Hawaii's Subaru or Gemini North telescope. First light for the new instrument is scheduled for 2013.

Clusters count

Galaxy clusters offer insights into the problem, too. One method exploits the fact that the CMB spectrum is distorted in characteristic ways when its microwave photons interact with the hot gas inside clusters. The phenomenon, which cools long-wavelength photons and energizes short-wavelength photons, is called the Sunyaev-Zeldovich effect (SZE).

The South Pole Telescope (SPT) is a millimeter- and submillimeter-wavelength instrument in Antarctica searching for this effect. SPT designers expect to discover up to 30,000 new clusters with masses greater than 100 trillion Suns.

Once the survey identifies targets, optical observers will measure the clusters' redshifts so astronomers can determine how the number of clusters changes as a function of redshift. This, in turn, will show how dark energy evolved as the universe aged: The number of clusters is sensitive to whether gravity or dark energy is the dominant cosmic force.

High-energy astronomers are doing something similar using facilities like NASA's Chandra X-ray Observatory. "We see the cluster gas directly with X rays, whereas the SZE approach sees how the gas affects the CMB," explains Stanford University's Steven Allen.

In December 2008, Chandra scientists announced that they independently determined dark energy's existence. They looked for dark energy's effects on the growth of galaxy clusters. Over time, dark energy's repulsive effect should put the brakes on the growth of such clusters by counteracting gravity's pull. The astronomers found that structure growth has slowed in the past 5 billion years, which is roughly when many scientists think dark energy kicked in.

Through a lens weakly

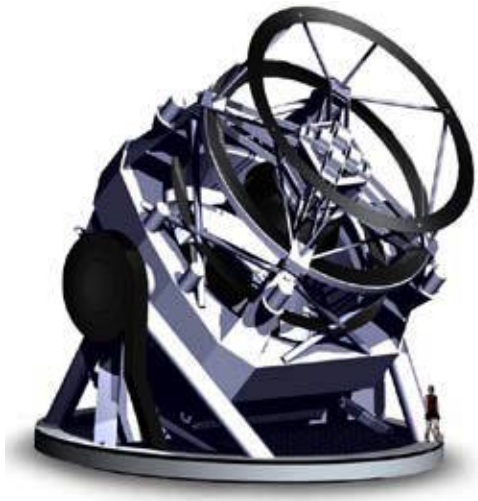
Any concentration of mass bends the light of galaxies behind it. Sometimes this occurs in spectacular fashion, producing rings or double images in the sky. So-called weak gravitational lensing is more common, causing subtle effects that can be observed only statistically. In regions where matter is clustered, galaxy shapes become stretched a tiny bit, say 1 percent. This modest shearing of galaxy images is detectable because it generally occurs in a single direction. But you have to look at millions or, preferably, billions of galaxies to see a pattern.

Because dark energy affects the universe's expansion rate, it affects the distances between the source, lensing galaxy, and us. By changing these distances, dark energy alters the distortion pattern's strength, which is something scientists can measure.

Astronomers first documented the phenomenon of cosmic shearing in 2000, so the technique is still new. The best effort, according to University of Pennsylvania physicist Gary Bernstein, involved a survey of about 2 million galaxies over 75 square degrees. "We're just starting to measure dark energy, but the more galaxies we get, the better we'll do," he says. "The goal is to see as much sky as possible."

The Canada-France-Hawaii Telescope Legacy Survey at Mauna Kea — a 5-year effort begun in 2003 — measured millions of galaxies over roughly 170 square degrees of sky. The 8.4-meter Large Synoptic Survey Telescope (LSST), scheduled to see first light in 2014 and begin science operations in 2015 at Cerro Pachón in northern Chile, is even more ambitious. This scope will survey a billion or so galaxies covering 30,000 square degrees. With this unparalleled combination of aperture and field of view, weak lensing — despite its name — could become powerful indeed.

> "WE'RE JUST STARTING to measure dark energy, but the more galaxies we get, the better we'll do."
> — *Gary Bernstein*



THE LARGE SYNOPTIC SURVEY TELESCOPE is a ground-based, wide-field, 8.4-meter instrument designed to image the entire available sky every 3 nights. Its superb images will help astronomers trace the shapes of remote galaxies — and see distortions produced by dark matter. This will provide an important and independent measure of dark energy. LSST CORPORATION

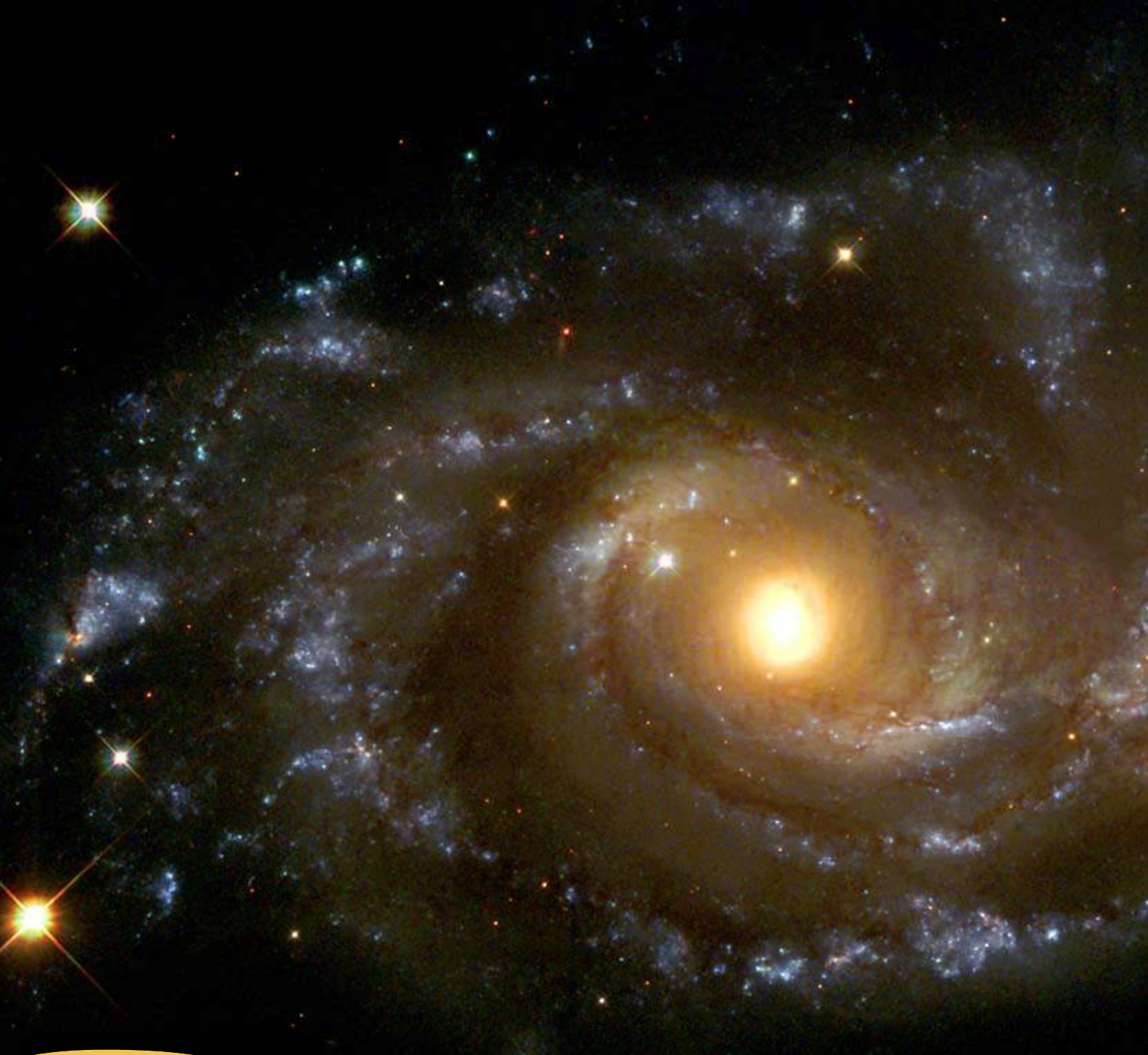
Grand synthesis

A proposal called the Dark Energy Survey would gather data on 300 million galaxies and merge all of these techniques into a coherent overview. "These techniques complement each other well," says Joshua Frieman of the University of Chicago. "They suffer from different sources of error, so if they agree, that gives you confidence in the result." The survey could begin in 2011 with observations from Cerro Tololo's 4-meter Blanco Telescope.

Harvard's Christopher Stubbs concurs. "Supernovae misbehaving at high redshift won't affect the density of clusters, nor will observations of large-scale-structure formation affect supernova luminosities."

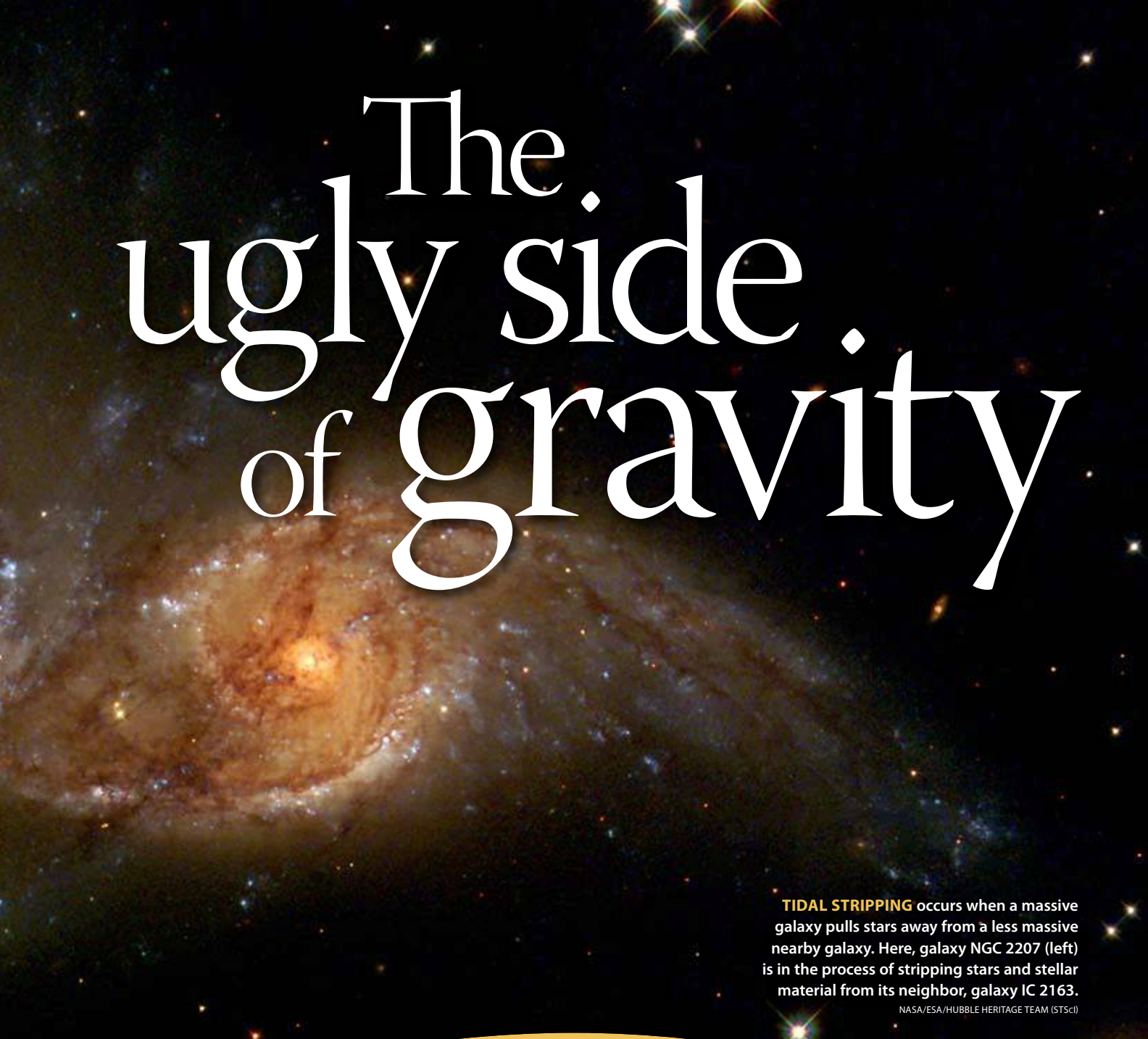
Owing to the difficulty in making these observations, no one will believe an answer unless it's obtained using more than one investigative method. Data so far show dark energy to be a much weaker form of Einstein's cosmological constant, but the precision isn't high enough to rule out other interpretations.

As California Institute of Technology cosmologist Sean Carroll puts it, "All we can do is keep improving the precision until we lose interest." Astronomers are far from that point now. "We are incredibly lucky to be working just at the moment when the pieces of the cosmic jigsaw puzzle are falling into place," he says. And dark energy constitutes the biggest puzzle piece of all.



Earth's ocean tides, Jupiter's comet-splitting power, and galaxies stripping stars away from neighbors tell the story of gravity's destructive force. /// **BY C. RENÉE JAMES**

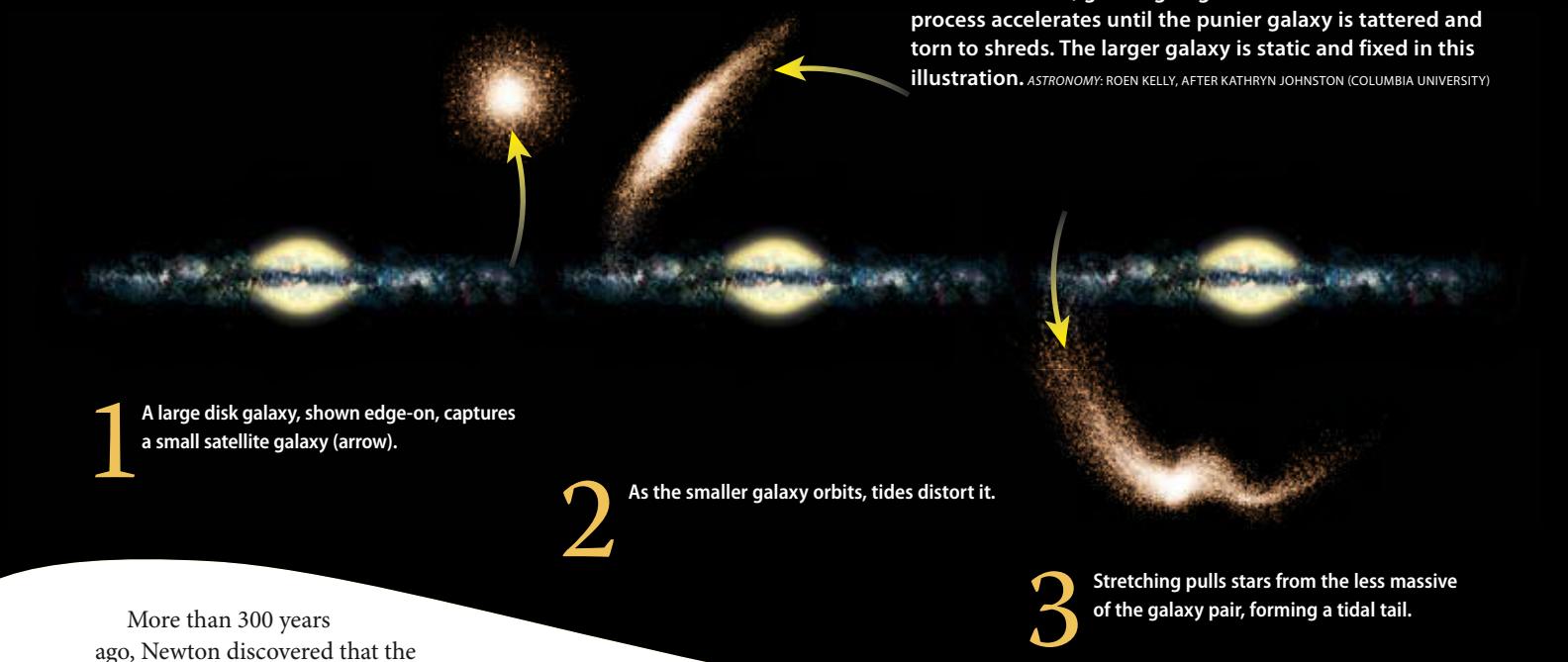
The ugly side of gravity



TIDAL STRIPPING occurs when a massive galaxy pulls stars away from a less massive nearby galaxy. Here, galaxy NGC 2207 (left) is in the process of stripping stars and stellar material from its neighbor, galaxy IC 2163.
NASA/ESA/HUBBLE HERITAGE TEAM (STScI)

Gravity is nature's weakest force. This might be difficult to believe when you step gingerly onto a scale, but keep in mind that you interact with Earth's entire 6.6 million trillion kilotons of mass in order to have that weight. Gravity is so weak that if it were the only thing holding you together, the faintest whisper of a breeze would tear you apart. Fortunately, your body is also strongly bound at the molecular level. For many objects in the universe, though, gravity is the only force holding them together. And, in some cases, gravity is the force that ultimately tears them apart.

How big galaxies shred small ones


1
A large disk galaxy, shown edge-on, captures a small satellite galaxy (arrow).
2
As the smaller galaxy orbits, tides distort it.
3
Stretching pulls stars from the less massive of the galaxy pair, forming a tidal tail.

TWO GALAXIES orbit one another in this illustration. The larger disk galaxy pulls stars from the smaller satellite galaxy into leading and trailing tails. The larger galaxy strips stars from the smaller, growing larger and more massive. The process accelerates until the punier galaxy is tattered and torn to shreds. The larger galaxy is static and fixed in this illustration. *ASTRONOMY:* ROEN KELLY, AFTER KATHRYN JOHNSTON (COLUMBIA UNIVERSITY)

More than 300 years ago, Newton discovered that the force of gravity depends on two things: the interacting bodies' masses — Earth and the Moon, for instance — and their separation. The farther apart the bodies, the weaker the gravitational attraction.

Earth and the Moon interact

Objects with mass don't experience gravity's tug uniformly over all their parts. For two orbiting bodies like Earth and the Moon, areas that face each other are also closer to one another and, thus, experience a larger gravitational pull.

As a result, the Moon tugs more strongly on the Moon-facing part of Earth than it does on the opposite side. This leaves a bulge behind on Earth's farside that is symmetric to the bulge pulled up on the moonward side. Earth also exerts a tidal force on the Moon. The same swollen lunar face always stares at us because the Moon is tidally locked to Earth.

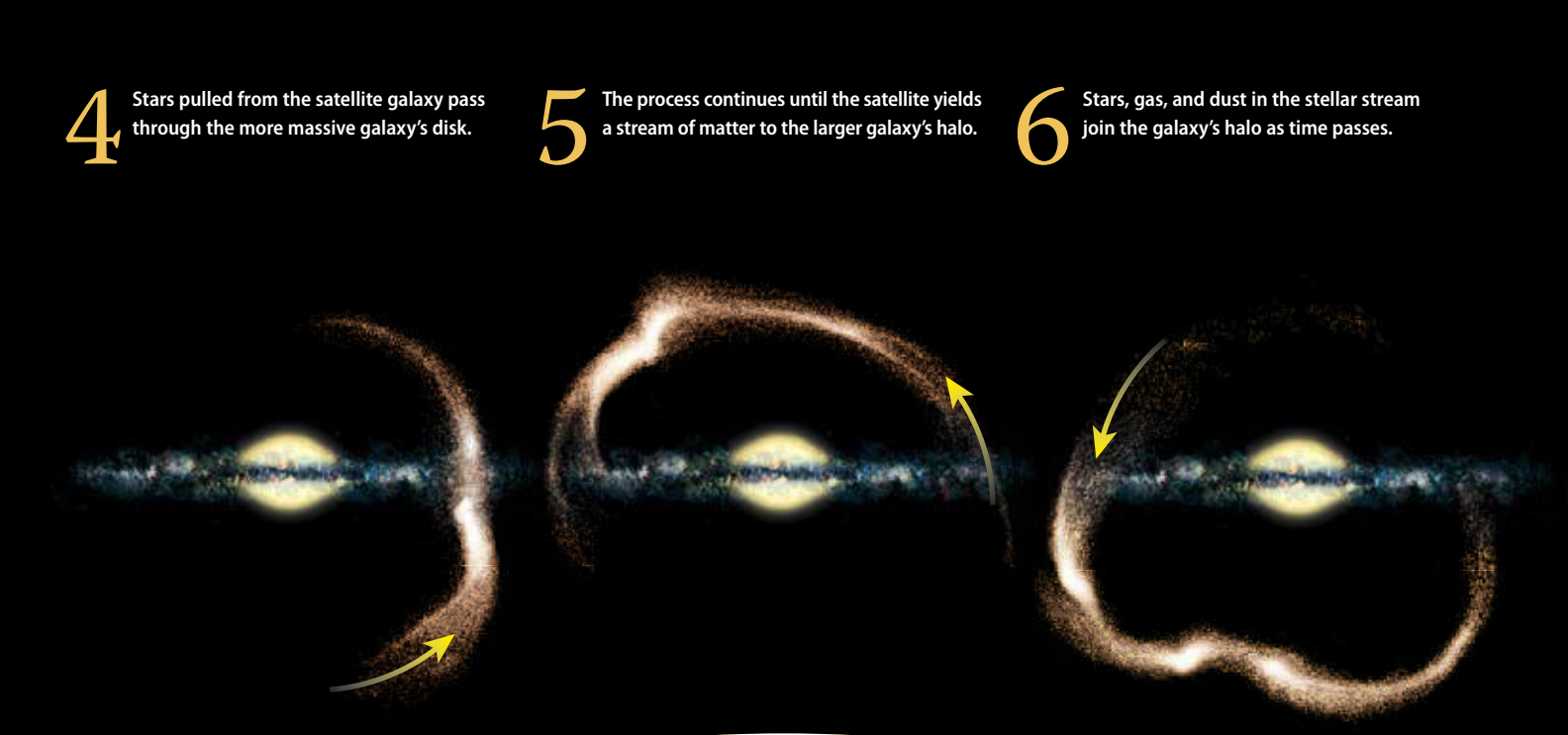
As ocean tides perpetually align with the Moon, which saunters around Earth every 27.3 days, Earth keeps spinning, once every 24 hours. The tidal bulges drag and create friction, which slows Earth's rotation at a rate of 2.3 milliseconds per day per century. That's not enough to change your work schedule, but it is enough to make us toss a leap second into our timekeeping every now and then.

These familiar ocean tides seem anything but destructive, except, perhaps, to sandcastles. Oceans aren't the only things tidal forces affect, though. The terra firma you stand on can rise more than a foot as the Moon passes overhead. The Sun contributes, too, but to a much lesser extent than the Moon because the Sun is much farther away. Twice a month — at New and Full Moon — the Sun and Moon give Earth an extra tidal squeeze. This tidal crunch is sometimes the last bit of stress a fault line can handle before it has to adjust itself. Then we see some indirect tidal destruction in the form of an earthquake.

Monster planet

But the tidal force between Earth and the Moon is insignificant compared to what Jupiter inflicts on its innermost moon, Io.

COMET SHOEMAKER-LEVY 9 experienced tidal disruption when it came close to massive Jupiter. The comet fragmented into at least 21 pieces before plummeting into the planet's dense atmosphere in July 1994. H. A. WEAVER AND T. E. SMITH (STScI)/NASA


4 Stars pulled from the satellite galaxy pass through the more massive galaxy's disk.
5 The process continues until the satellite yields a stream of matter to the larger galaxy's halo.
6 Stars, gas, and dust in the stellar stream join the galaxy's halo as time passes.

Our Moon contains a scant 1 percent of Earth's mass and lies 239,000 miles (385,000 kilometers) away. Io, about 20 percent more massive than the Moon, has to contend with a planet 318 times Earth's mass. And Io is only 23,000 miles (37,000 km) farther away. Additional tidal forces come from the other three Galilean satellites: Europa, Ganymede, and Callisto. Their masses are 0.66, 2.03, and 1.45 Moon masses, respectively. Each is engaged in its own tidal tug of war with Jupiter and with its neighboring satellites. They all distort Io when their orbital dance around Jupiter brings them within range.

As a result, Io has a tidal bulge reaching hundreds of feet (tens of meters) high and an unstable landscape that spews volcanic plumes more than 100 miles (160 km) into space. Although our Moon keeps the same face toward Earth, Io cannot become tidally locked to Jupiter. The moon's orbit is too eccentric, and its siblings add stresses that prevent it from achieving synchronous rotation. Io's continual deformation heats its interior and powers its volcanoes. In this erratic terrain, mountains grow and collapse within a few million years.

Although farther from Jupiter, Europa also feels these tidal tugs. But because tidal

C. Renée James *is an associate professor of physics at Sam Houston State University in Huntsville, Texas.*

LINKING OCEAN TIDES AND THE MOON

Modern-day astronomers study tidal forces arising from gravitational attraction to help them understand everything from the structure of comets to the evolution of galaxies. But the link between ocean tides and the Moon wasn't always so well-known, although ancient philosophers had some interesting ideas as to their cause.

OCEAN TIDES result from the gravitational force between Earth and the Moon. Gravity's pull exists among all objects in the universe. MIKE LE

More than 2,300 years ago, Aristotle (384–322 B.C.) seemed to understand the link between the Moon and ocean tides. Unfortunately, he also attributed tidal variations to the sea demon Charybdis.

In 1616, Italian astronomer and physicist Galileo Galilei (1564–1642) wrote *Treatise on the Tides*. In it, he sought to divorce natural motions from unseen supernatural forces like sea demons by attributing observable effects to observable causes. He asserted that the 25-hour tidal cycle was proof of Earth's rotation and motion around the Sun — an incorrect hypothesis. He ultimately dismissed as mysticism writings by Johannes Kepler (1571–1630) and others that suggested a tide-Moon link.

In 1687, English mathematician and physicist Isaac Newton (1643–1727) suggested Earth's tides are the result of gravity — an attractive force between bodies in space that can distort, deform, and even break apart massive objects, including our home planet. Newton's breakthrough theory of gravitation, published in 1687's *Principia*, explained the tides as the action-at-a-distance force of gravity. This gravitational force exists between all objects throughout the universe but diminishes as the distance between objects increases.

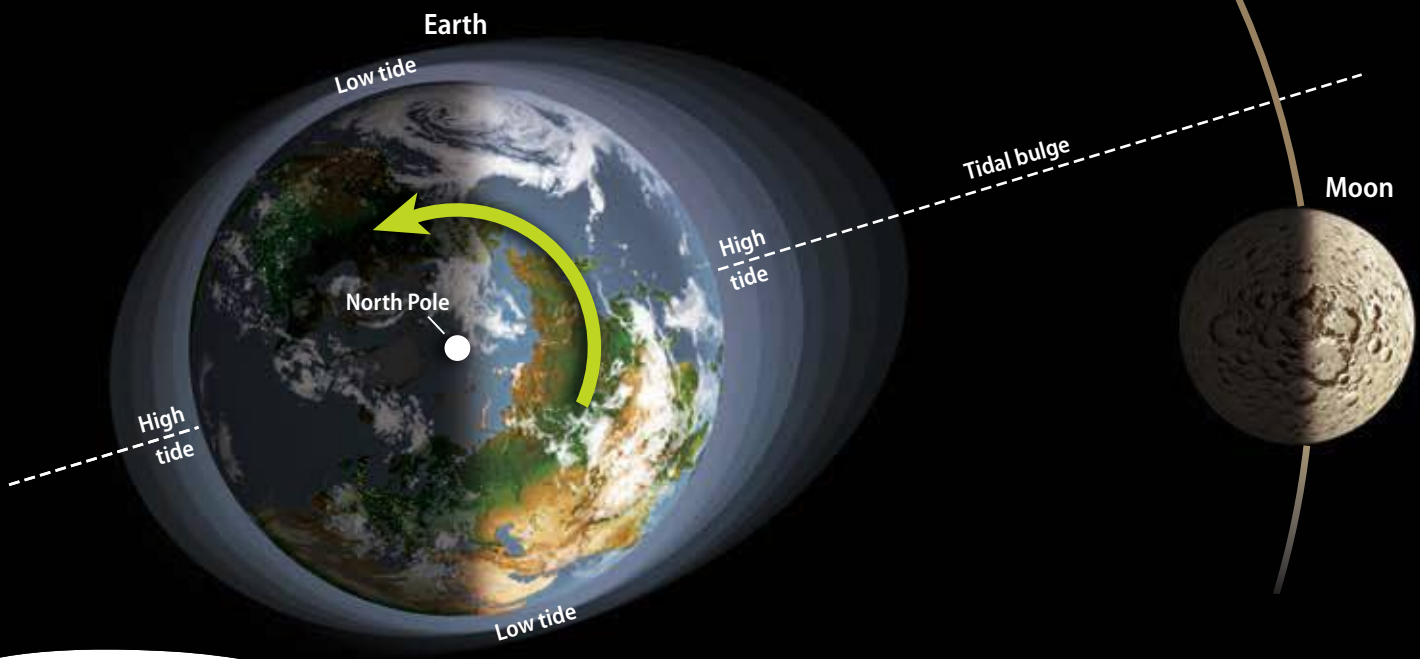
In 1882, Lord Kelvin (1824–1907) spoke about the topic of tidal theory to the British Association at its Southampton meeting. Kelvin noted the periodicity of ocean tides and asserted his belief that "Tides are motions of water on the Earth due to the attractions of the Sun and the Moon."

After years of studying the continuous nature of ocean tides, scientists now know much about the link between ocean tides and the Moon. What scientists have learned about tidal forces helps them learn even more about tidal effects in the universe. — *C. R. J.*

The Earth-Moon connection

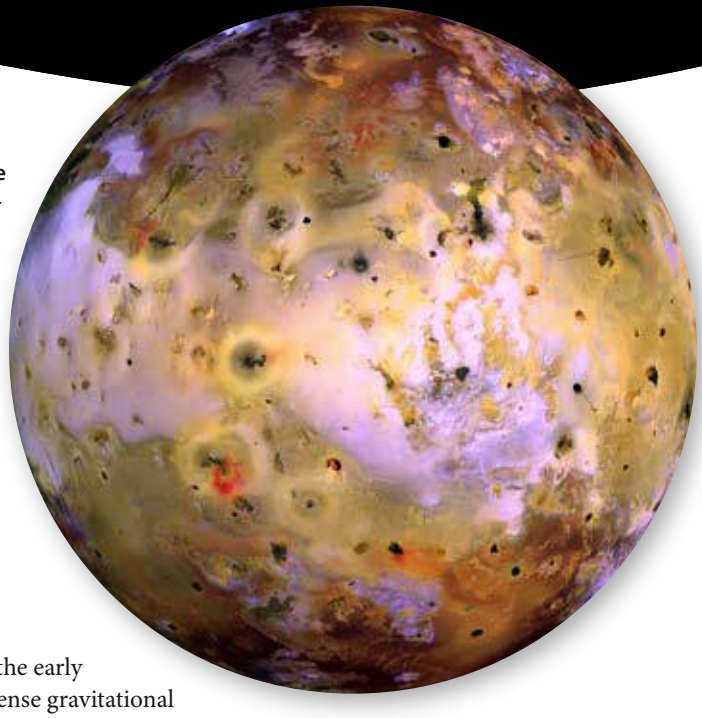
THE MOON is tidally locked to Earth in a gravitational dance. As the Moon orbits, it pulls more on closer areas than those farther away. This asymmetrical pulling forms tides on Earth. (This Illustration is not to scale.)

ASTRONOMY: ROEN KELLY



forces plummet with increasing distance, Europa experiences gentler stresses. Still, they have helped shape what is quite possibly the most intriguing body in the solar system. The same tidal heating that wreaks havoc on Io apparently makes Europa a cosmic slushy with a 62-mile-thick (100 km) layer of water and ice sealed beneath an icy crust. If there's a place in the solar system, in addition to Earth, with the raw ingredients for life, Europa is it.

Tidal forces become less bearable for objects closer to Jupiter than Io. As objects held together solely by their own gravity come to within about 3.5 Jupiter radii, or 155,000 miles (250,000 km), of the massive planet, they cannot withstand the tidal stresses and break apart like Comet Shoemaker-Levy 9 did in 1994.



IO, JUPITER'S INNERMOST MOON, feels the full force of Jupiter's tidal pull on one side and that of the massive planet's three large satellites, Europa, Ganymede, and Callisto, on the other. This tidal tug of war makes Io the most geologically active body in the solar system, with mega volcanoes, bulges that rise 300 feet (100 meters), and surface fractures.

NASA/JPL-CALTECH

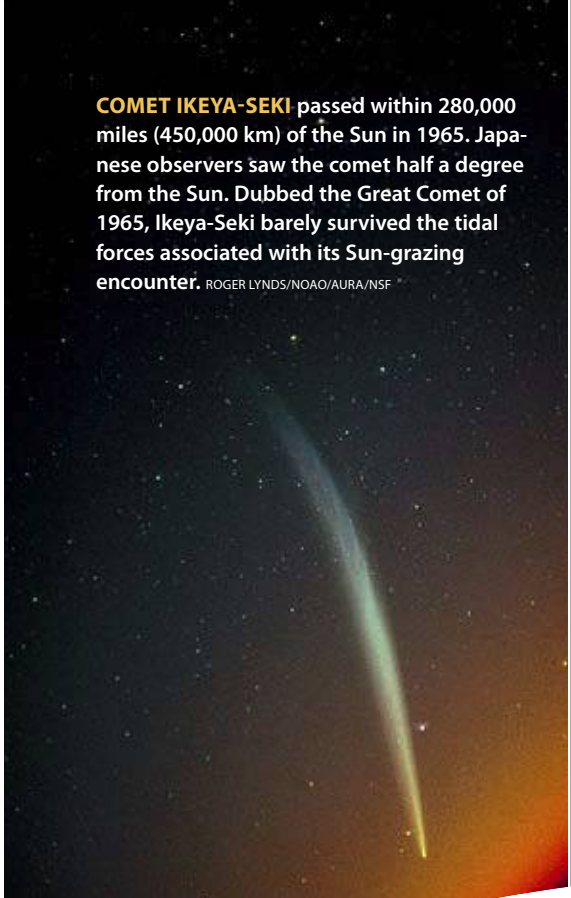
A comet's bad day

Comets that repeatedly pass close to the Sun get destroyed over time. Heat and energetic solar wind slowly erode a comet, littering the solar system with debris that may eventually become a terrestrial meteor shower.

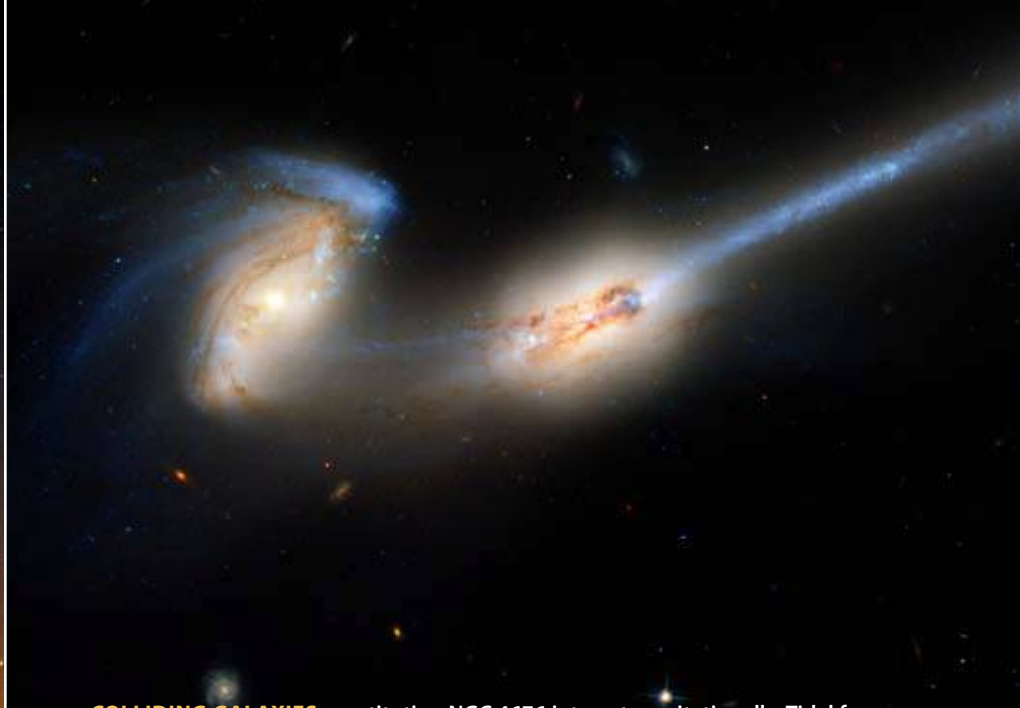
Comet Shoemaker-Levy 9 — a loosely bound heap of ice, rock, and dust — was probably once a short-period, Sun-orbiting comet. Its aphelion swing away from the Sun, likely in the 1920s or 1930s, put it close enough to Jupiter in the early 1970s for the planet's immense gravitational field to capture it. SL9 became the first jovian comet-turned-satellite known, orbiting the gas giant until its spectacular, disintegrating demise in July 1994.

Before its brush with Jupiter, SL9 seemed to be in a cometary "safe zone" some 466 million miles (750 million km) away from the Sun. But once caught in Jupiter's gravitational field, it began a highly eccentric orbit around the solar system's largest planet, skimming 24,800 miles (40,000 km) above the cloud tops at its July 1992 closest approach.

The 3-mile-wide (5 km) ball of ice and rock fragmented when it came to within 1.3 times Jupiter's radius. SL9's Jupiter-facing side was closer to the planet and subjected



COMET IKEYA-SEKI passed within 280,000 miles (450,000 km) of the Sun in 1965. Japanese observers saw the comet half a degree from the Sun. Dubbed the Great Comet of 1965, Ikeya-Seki barely survived the tidal forces associated with its Sun-grazing encounter. ROGER LYNDS/NOAO/AURA/NSF



COLLIDING GALAXIES constituting NGC 4676 interact gravitationally. Tidal forces pull stars and gas into a long tidal tail (upper right). Matter also streams between the two galaxies. Hubble's Advanced Camera for Surveys captured this image of NGC 4676, nicknamed "The Mice," some 300 million light-years away in Coma Berenices.
NASA/H. FORD (JHU)/G. ILLINGWORTH (UCSC/LO)/M. CLAMPIN (STScI)/G. HARTIG (STScI)/ACS SCIENCE TEAM/ESA

to a harder pull than its farside. Gravity's larger tug on its Jupiter-facing side surpassed the comet's ability to hold itself together. As a result, SL9 fragmented into more than 20 smaller comets. At their next jovian approach, in July 1994, the icy comet fragments dove one by one into Jupiter's thick atmosphere.

The culprit was neither atmospheric friction — which makes for the awesome splintering meteors observed on Earth — nor solar heat. The problem for SL9 was gravity, a force we usually think of as holding things together. What killed Shoemaker-Levy 9 was Jupiter's tidal force, which, according to Jet Propulsion Laboratory Senior Research Scientist Donald Yeomans, was quite modest and indicates how fragile comets are.

Jupiter is by no means the most massive object around. The Sun has also tidally split comets, including the Great September Comet of 1882 and Ikeya-Seki in 1965. But even the Sun's tidal reach is puny compared to that of an entire galaxy. On this grand scale, we find galaxies throwing their weight around, shredding interlopers and assimilating them.

Galactic tides

The Milky Way, for instance, contains a trillion solar masses, most of which is invisible. A hapless globular cluster or small galaxy hosting anywhere from a few hundred thousand to tens of millions of suns will inevitably lose the tug of war with the Milky Way if it strays too close.

As the smaller galaxy approaches, stars closest to the Milky Way will be stripped away. They will stream away in a tidal tail and settle into orbit about our galaxy. The small satellite galaxy, having lost some of its mass and, thus, some of its self-gravity, will weaken its grip on the rest of its stars. This makes it even easier for the Milky Way to strip more material from it. Eventually, the smaller system will look as though it's been run through a taffy puller, stretched beyond recognition as tidal streams wrap around the Milky Way. Ultimately, the smaller galaxy's material will merge into our own galactic traffic pattern.

This is what appears to have happened throughout much of the Milky Way's history, as well as in most other galaxies. Advances in photometry, wide-field imaging, and computing have helped astronomers discover tidal tails pulled from smaller galaxies and globular clusters amid a noisy background of field stars.

These stretching systems tell us not only about the galaxy being shredded — how much mysterious dark matter it contains, for instance — but also about the Milky Way.

Because stellar tidal streams maintain a well-behaved galactic orbit, they can help astronomers pinpoint the center of the galaxy in much the same way as mapping globular clusters helped American astronomer Harlow Shapley estimate the extent of the Milky Way about 90 years ago.

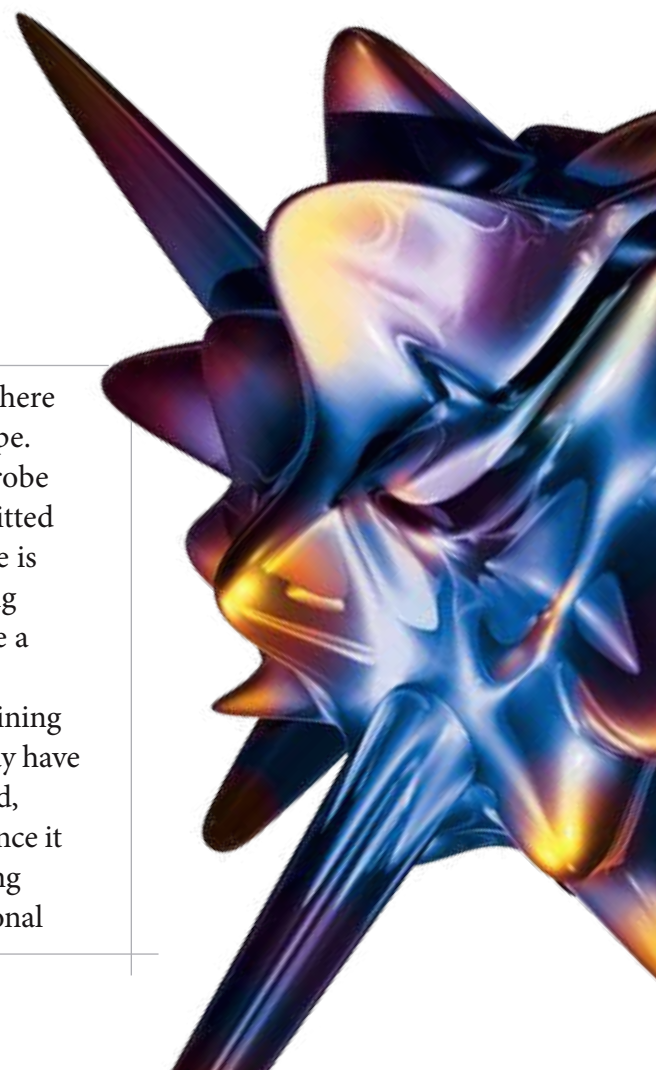
Astronomers have just begun applying data from tidal streams to determine the Sun's precise distance from the galactic center and the exact orbital speeds of stars in our locale. The Sagittarius dwarf galaxy is particularly helpful in this regard because its tidal stream spans nearly a full orbit around the Milky Way. This means it has been completely tidally disrupted over the past 4 to 6 billion years.

Galileo could not have imagined the scope of the force that nudges water up and down beaches. The ideas of a planet reaching out an invisible hand to shred a passing comet or of a galaxy spending Earth's lifetime stretching an interloping star system would have been as fanciful to him as, well, a sea demon.

And the next time it feels as though the forces of life are about to pull you apart, keep an eye on your sandcastle and remember this: Compared to many objects in the universe, you really have it together.

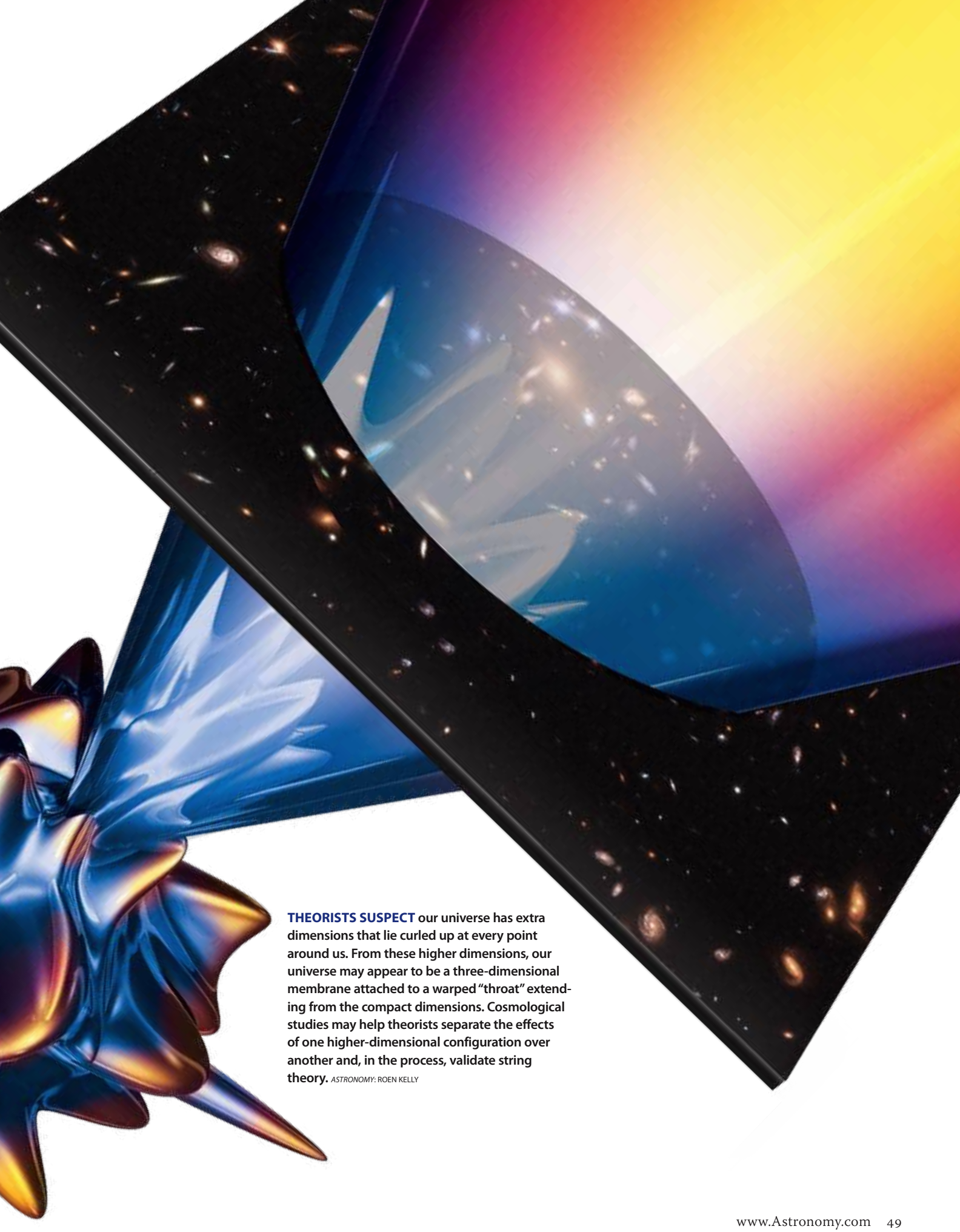
Searching for the shape of the universe

Inflation, an early period of cosmic hyper-expansion, may be the key to proving the universe has six extra dimensions. /// **BY STEVE NADIS**



For as long as people have studied the sky and wondered where it ends, or how, they've wondered about the universe's shape. Information from the Wilkinson Microwave Anisotropy Probe (WMAP), which is mapping the whisper of microwaves emitted 380,000 years after the universe's birth, indicates the universe is flat to within a 2 percent margin of error. If the universe is big enough, the cosmos could appear flat whether it's shaped like a pancake, a meatball, or a bagel.

But "outer space" — the seemingly immeasurable gulf containing billions of galaxies — isn't the only part of the universe that may have shape. Physicists say there's also an "inner space" — a concealed, microscopic realm tucked away so tightly that we can't experience it directly. It's here that string theory, often regarded as our leading explanation of nature, postulates the presence of a 10-dimensional

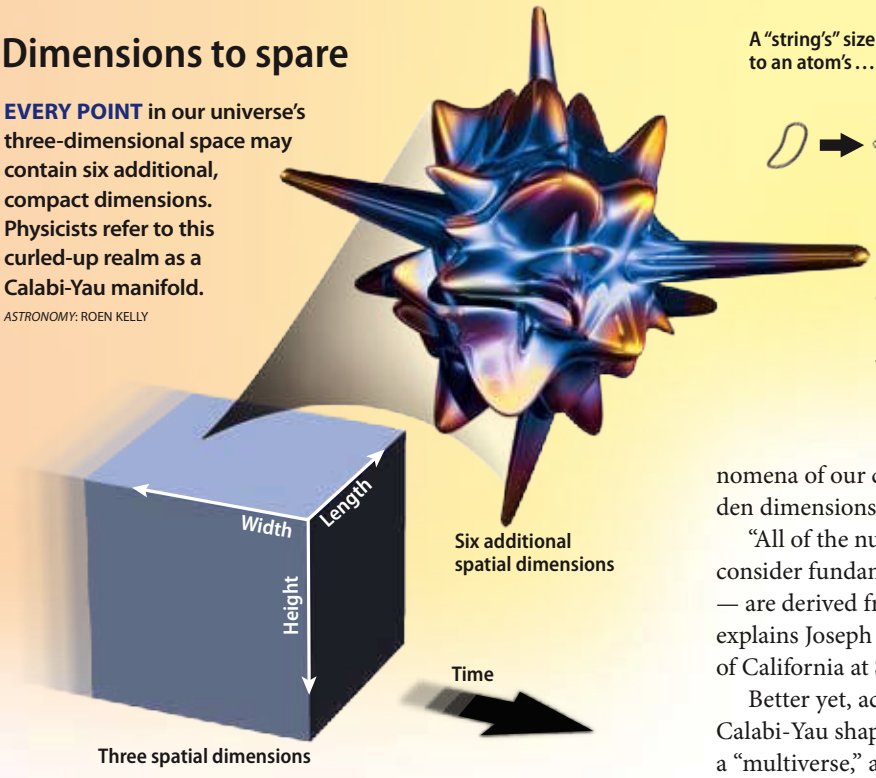


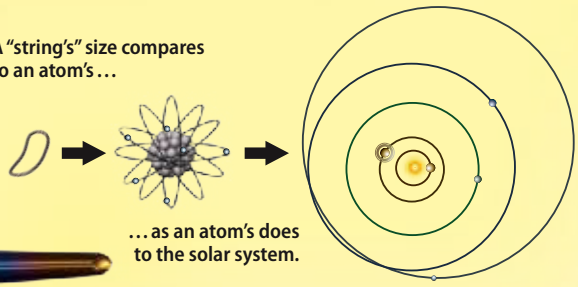
THEORISTS SUSPECT our universe has extra dimensions that lie curled up at every point around us. From these higher dimensions, our universe may appear to be a three-dimensional membrane attached to a warped "throat" extending from the compact dimensions. Cosmological studies may help theorists separate the effects of one higher-dimensional configuration over another and, in the process, validate string theory. *ASTRONOMY*: ROEN KELLY

Dimensions to spare

EVERY POINT in our universe's three-dimensional space may contain six additional, compact dimensions. Physicists refer to this curled-up realm as a Calabi-Yau manifold.

ASTRONOMY: ROEN KELLY





THE TWISTED DIMENSIONS of Calabi-Yau manifolds may be similar in size to superstring theory's hypothetical strings. *ASTRONOMY*: ROEN KELLY

universe — the normal three dimensions of space we're familiar with, plus time, plus six other dimensions.

Six pack

A century ago, Einstein's general theory of relativity unified space and time as four-dimensional "space-time." So where do string theory's extra dimensions reside? According to scientists, they're curled up into tiny geometrical containers called Calabi-Yau manifolds, where they remain forever hidden from us.

"If string theorists are right," says Harvard University physicist Lisa Randall, "everywhere in visible space — at the tip of your nose, at the north pole of Venus, at the spot above the tennis court where your racket hit the ball the last time you served — there would be a six-dimensional Calabi-Yau manifold of invisibly tiny size." This higher-dimensional geometry therefore exists at every point in space.

Physicists classify these intricate, twisted, geometric forms as compact —"something you can put in the trunk of your car," they often say. That's a bit of scientific understatement meant to convey that Calabi-Yau manifolds have no infinitely long structures.

Their actual size remains an open question. Physicists initially regarded them as exceedingly small, with diameters on the order of the Planck scale (10^{-33} centimeters). Current thinking holds they're 10,000 trillion times larger than this, perhaps similar to the spatial scale of string theory's hypothesized strings — larger, perhaps, but still too small to detect.

Theorists are keenly interested in the shape of these complex, six-dimensional spaces. They believe the manifold's geometry dictates the laws of particle physics and influences gravity, cosmic inflation, and dark energy. If they're right, these dominant phenomena of our cosmos may either spring directly from these hidden dimensions or be profoundly affected by them.

"All of the numbers we measure in nature — all of the things we consider fundamental, such as the masses of quarks and electrons — are derived from the size and shape of Calabi-Yau space," explains Joseph Polchinski, a theoretical physicist at the University of California at Santa Barbara.

Better yet, according to string theory, the number of possible Calabi-Yau shapes is linked to the number of possible universes — a "multiverse," as it's sometimes called. In fact, many of today's biggest problems in physics and cosmology reduce to a single geometry problem: determining the shape of extra dimensions.

So, what can we learn about inner space's geometry? Investigators have two main goals: to secure evidence for the existence of these dimensions and to obtain hints about their underlying geometry. The picture is still crude. Researchers have described these shapes, or parts of them, as ice cream cones, throats, cigars, gloves, and even anteaters.

"How are the extra dimensions of string theory curled up?" asks University of Wisconsin-Madison physicist Gary Shiu. He leads a team of researchers who think they've hit on a way to answer this question. "We argue that precise measurements of the cosmic microwave background [CMB] can give us clues," he says.

BRANES, STRINGS, AND THE CMB

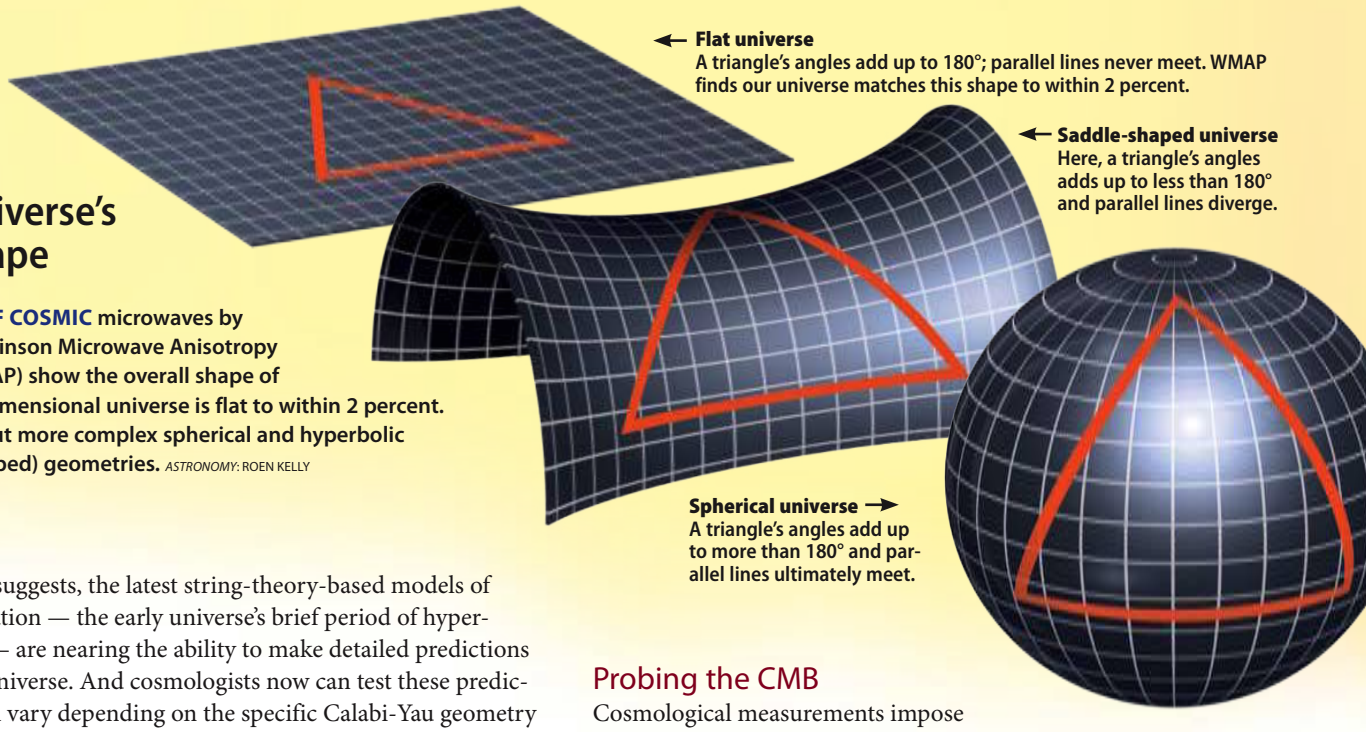
BRANE
Any of the extended objects that arise in string theory. A 1-brane is a string, a 2-brane is a membrane, and a 3-brane has three spatial dimensions.

COSMIC MICROWAVE BACKGROUND (CMB)
Microwave radiation permeating the universe that was originally released about 380,000 years after the Big Bang.

STANDARD MODEL
A theory of interactions of nature's most fundamental known particles (i.e., electrons and quarks) developed in the late 1960s and early 1970s. Its inability to explain gravity suggests a more fundamental theory exists.

STRING THEORY
A shorthand term for the unified "superstring theory," which postulates that nature's fundamental ingredients are not particles; instead, they are one-dimensional filaments called "strings." String theory unites quantum mechanics and general relativity, which are otherwise incompatible.

Steve Nadis *is a contributing editor of* Astronomy. *He's working with Harvard University's Shing-Tung Yau on a book tentatively titled* The Shape of Inner Space.


Flat universe
A triangle's angles add up to 180°; parallel lines never meet. WMAP finds our universe matches this shape to within 2 percent.
Saddle-shaped universe
Here, a triangle's angles adds up to less than 180° and parallel lines diverge.
Spherical universe
A triangle's angles add up to more than 180° and parallel lines ultimately meet.

The universe's 3-D shape

STUDIES OF COSMIC microwaves by NASA'S Wilkinson Microwave Anisotropy Probe (WMAP) show the overall shape of our three-dimensional universe is flat to within 2 percent. This rules out more complex spherical and hyperbolic (saddle-shaped) geometries. *ASTRONOMY:* ROEN KELLY

As Shiu suggests, the latest string-theory-based models of cosmic inflation — the early universe's brief period of hyper-expansion — are nearing the ability to make detailed predictions about our universe. And cosmologists now can test these predictions, which vary depending on the specific Calabi-Yau geometry assumed responsible for inflation's birth, against CMB data.

Brane damage

The basic premise is that the motions and interactions of large, membrane-like structures called "branes" actually drove cosmic inflation. In this scenario, a brane and its opposite counterpart, an antibrane, slowly move toward each other in higher dimensions.

The two branes possess a mutual attraction, so their separation represents a vast source of potential energy — enough to trigger inflation. This fleeting process, which expanded our four-dimensional universe by more than a trillion trillion times, continued until the branes collided and annihilated each other. In this view, inflation occurs before the Big Bang. In fact, it's the energy released in the branes' mutual destruction that created and powered our Big Bang.

So the thing we've traditionally called our universe sits on a three-dimensional brane that would be a mere speck, or point, in a six-dimensional Calabi-Yau manifold. But how can our vast — and apparently infinite — cosmos fit into higher-dimensional space's ultracompact domain? Researchers say our three spatial dimensions are independent of the Calabi-Yau dimensions.

"Rather than pointing in the same direction, they point in orthogonal [forming a right angle] directions, so there's no trouble fitting in," explains Cornell University physicist Liam McAllister. Adds McAllister's Cornell colleague Henry Tye, "We're just sitting in a tiny corner of six-dimensional space."

The brane and antibrane responsible for inflation moved around in the early universe. "The fact that the branes have been moving allows us to learn much more about that space than just sitting in the corner," Tye says. "Just like at a cocktail party: You don't pick up much if you stay in one corner. But if you move around, you're bound to learn more." As it turns out, brane movement prior to inflation leaves an indelible — and potentially observable — imprint on the CMB.

The dominant phenomena of our cosmos may spring directly from *hidden dimensions* or be profoundly affected by them.

Probing the CMB

Cosmological measurements impose constraints on the kind of Calabi-Yau space we live in. Observational data are now getting precise enough that researchers can determine whether a given Calabi-Yau manifold is consistent with experiment, a development physicists find encouraging.

"You can take inflation models and divide them in half — those that are favored by observations and those that are not," says physicist Cliff Burgess of Ontario's Perimeter Institute for Theoretical Physics. "The fact that we can now distinguish between inflation models means we can also distinguish between the geometric constructions that give rise to those models."

For example, a 2006 study led by McAllister explored the observational signals of inflation occurring in an extended portion of a Calabi-Yau manifold called a "warped throat." The scientists found that different Calabi-Yau geometries lead to different observational signatures.

Ice cream cones and anteaters

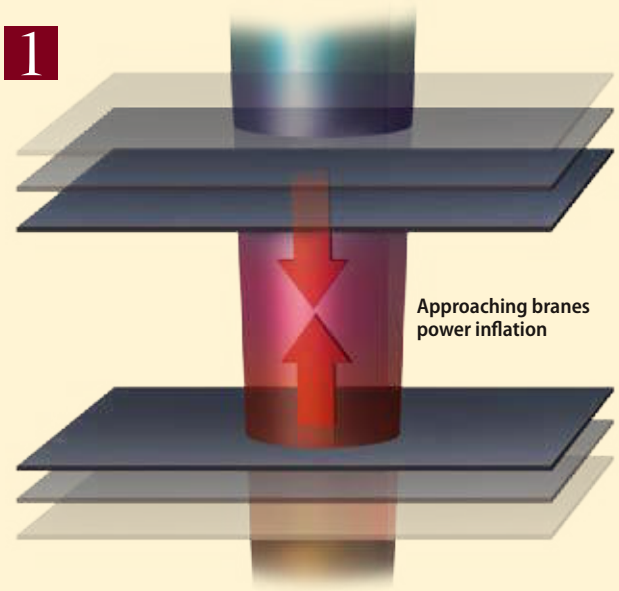
A "throat" is the most common defect found in Calabi-Yau space. It's a cone-shaped bump that naturally protrudes from the surface. McAllister suggests the image is reminiscent of a large scoop of ice cream consisting of the bulk of those tightly wrapped dimensions, all sitting atop a slender cone.

This throat becomes even more distended and warped by the magnetic fields, or fluxes, predicted by string theory. "The flux exerts a force on the tip of the cone, stretching it out into a long, narrow neck like the snout of an anteater," explains Stanford University physicist Leonard Susskind.

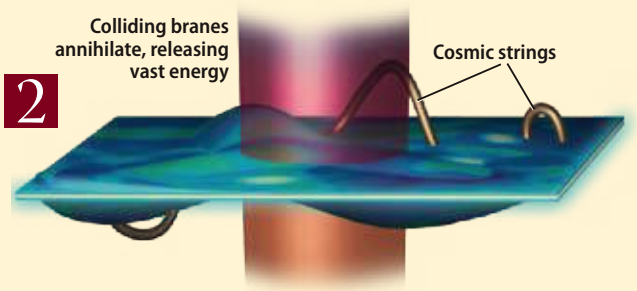
Any given Calabi-Yau space is likely to have more than one warped throat, so Cornell University astronomer Rachel Bean prefers the analogy of a rubber glove to that of an ice cream cone. "Our three-dimensional universe is like a dot moving down the finger of a glove," she explains. Inflation ends when the brane, or

Did annihilating branes trigger the Big Bang?

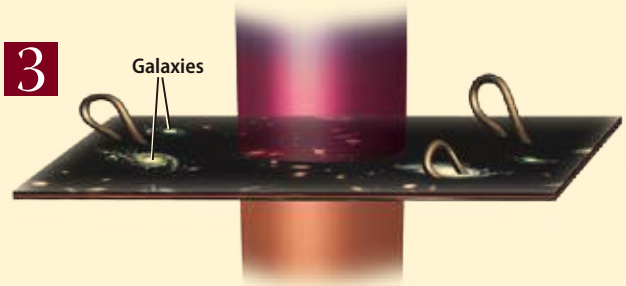
Physicists suggest a brane-antibrane pair interacted to create the Big Bang. Here's how it might have worked:



▲ **A brane and an antibrane spanning our universe's three spatial dimensions move together. As they approach, inflation begins. The size of the universe grows a trillion trillion times and possibly creates ripples in space-time called gravitational waves.**



▲ **Inflation ends when the branes collide and annihilate each other. The energy release heats up our universe, initiating the hot Big Bang. The collision may also create cosmic strings. Such structures may reveal themselves by gravitational lensing of distant background objects or by polarizing the CMB.**



▲ **Density fluctuations produced during inflation become the seeds for today's cosmic structures. They also created the temperature fluctuations now being mapped in the CMB.**

ASTRONOMY: ROEN KELLY

"dot," reaches the finger's tip, where an antibrane — or a stack of antibranes — patiently waits. Because the finger's shape constrains the brane's motion, she says, the specific features of inflation stem from its geometry.

Suppose inflation occurred within the confines of two different warped-throat geometries. Could we tell them apart? In a 2007 study, Shiu and his then-graduate student Bret Underwood (now at McGill University in Montreal) chose two relatively well-known throat models named Klebanov-Strassler and Randall-Sundrum. The scientists then looked at how inflation under those two different conditions would affect the CMB.

In particular, they focused on a standard CMB measurement: temperature fluctuations in the early universe. These fluctuations should appear roughly the same on small and large scales. Scientists call the rate at which these fluctuations change from small to large scales the "spectral index." Shiu and Underwood found a 1 percent spectral-index difference between the two scenarios. So, the choice of geometry has a measurable effect on that number.

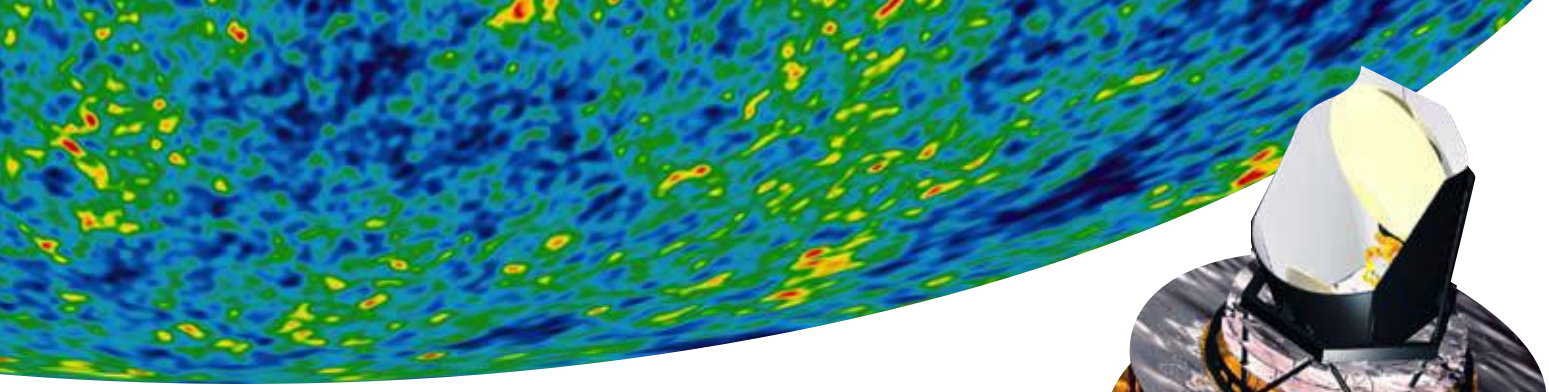
In cosmology, a 1 percent difference can be significant. The European Space Agency's Planck spacecraft — the latest CMB mapper launched in May 2009 — could measure such differences. Planck data may allow one throat geometry as a possible shape for higher dimensions and eliminate another.

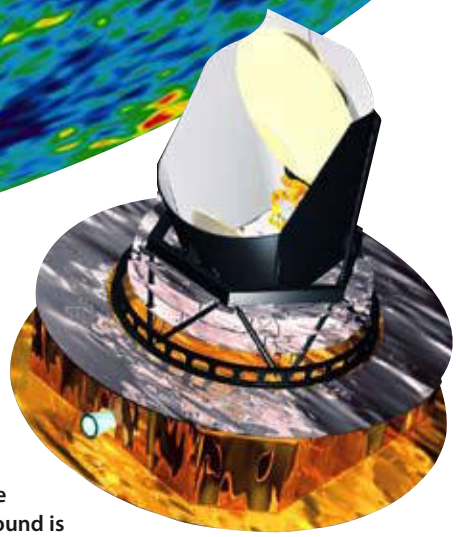
"Away from the tip, the two geometries look almost identical, and people used to think they could be used interchangeably," Underwood notes. "Shiu and I showed that the details do matter." Still, he admits that going from the spectral index, which is a single number, to the geometry of extra dimensions is a big leap.

If researchers have enough data on the CMB, can they determine what Calabi-Yau shape it is? Burgess doesn't think this will be possible in the next 2 decades. McAllister also is skeptical. "We'll be lucky in the next decade just to be able to say inflation did or did not occur," he says. "I don't think we'll get enough experimental data to flush out the full shape of the Calabi-Yau space, though we might be able to learn what kind of throat it has or how many branes it has."

Shiu is more hopeful. "If you can only measure the spectral index, it's hard to say something definitive about the geometry," he says. But you'd get much more information if you could measure non-Gaussian features of the CMB — ways in which matter's clumpiness in the early universe deviates from a purely random distribution. A clear indication of this would impose more constraints on the underlying geometry. "Instead of one number, like the spectral index, it's a whole function — a whole bunch of numbers that are all related to each other," he adds.

If matter were particularly clumpy, it could point to a specific version of brane inflation known as Dirac-Born-Infeld (DBI) occurring within a well-defined throat geometry. "Depending on the precision of the experiment," Shiu says, "such a finding could, in fact, be definitive."





THE EUROPEAN Space Agency's Planck spacecraft (right) launched in May 2009. The satellite's high-resolution view of the cosmic microwave background is designed to exceed WMAP's (above). With enough detail, physicists could determine which possible Calabi-Yau geometries our universe cannot contain.

CMB IMAGE AT TOP: NASA/WMAP SCIENCE TEAM; PLANCK SPACECRAFT: ESA

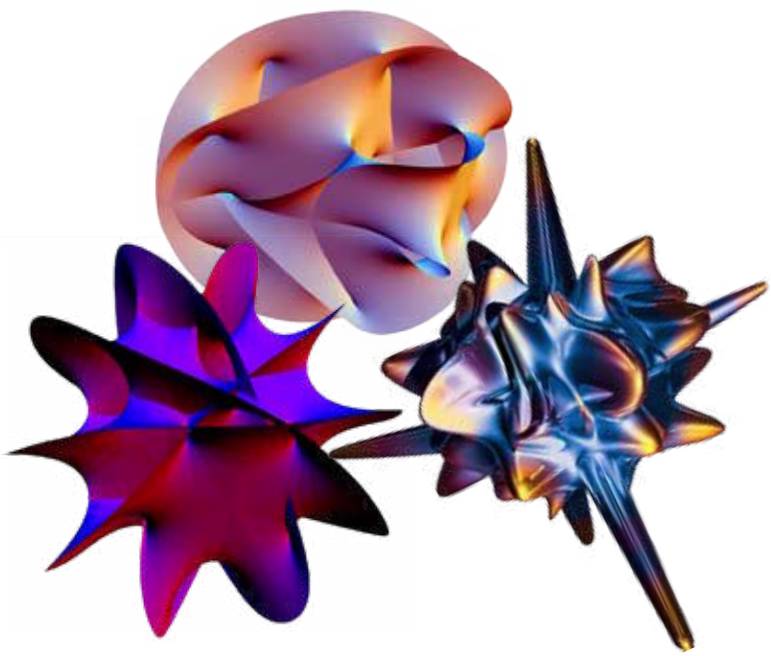
Columbia University physicist Sarah Shandera notes that a string-theory-motivated inflation model like DBI may prove important even if string theory fails as the ultimate description of nature. "It gives cosmologists something new to look for," she says. As in any experimental science, knowing what questions to ask, and how to frame them, is a big part of cosmology's game.

In the abstract realm of theoretical physics, warped throats are considered both fundamental and generic. They're features "that arise naturally from six-dimensional Calabi-Yau space," according to Princeton's Igor Klebanov. "No one can say how the universe works, yet I still think warped throats are a crucial part of the geometry of nature," he says. That belief may or may not be true, but warped throats offer theorists a setting rich in possibilities.

Strings across the cosmos

If inflation's driving force originated in a warped throat, then gravitational waves — ripples in the fabric of space-time — might bear clues about the specific manifold that generated them. Inflation should have created such waves, but no one's detected them yet.

Hypothetical defects in space called cosmic strings, produced at the end of inflation, might yield even more telling signals. Cosmic strings resemble superstrings in their basic properties — except for size, as they can span the entire universe. Their presence would leave a distinct pattern in the CMB. "The details of that signature would depend on the shape of the extra dimensions," Polchinski says.



CALABI-YAU MANIFOLDS wrap their extra dimensions in a variety of shapes. No one knows which geometry best describes our universe, but cosmology may help narrow down the possibilities.

TOP AND LEFT: ANDREW J. HANSON (INDIANA UNIV.); RIGHT: *ASTRONOMY*: ROEN KELLY

Warped-throat inflation models predict a spectrum of cosmic strings formed in brane-antibrane annihilations. The strings would have a range of tensions, similar to the properties of rubber bands of varying thicknesses. "Evidence of different types of cosmic strings would be a truly dramatic finding," Klebanov adds.

Getting a handle on the shape of Calabi-Yau space will require precise measurements of the CMB's spectral index, sightings of non-Gaussian clumping, and the detection of gravitational waves or cosmic strings. "Although we now have confidence in the standard model of physics, that model did not materialize overnight," Shiu notes. "It came from a whole sequence of experiments over the course of many years. In this case, we'll need to bring a lot of measurements together to get an idea of whether extra dimensions exist or whether string theory seems to be behind it all."

Patience, Shiu says, is also in order because researchers' overall goal is not just to probe the geometry of hidden dimensions. They also want to put to the test string theory itself, a branch of physics that has been criticized for lacking experimental support. The general strategy makes sense to Underwood. He considers cosmology one of the most promising ways to test string theory because the energy scale of inflation is close to the energy scale needed to make strings.

"It's possible that string theory will predict a finite class of models, none of which are consistent with inflation," McAllister says, "in which case we could say the theory is excluded by observation. Some models already have been excluded, which is exciting because it means the cutting-edge data really make a difference." At the moment, he says, warped-throat inflation is one of the best models produced so far, but, he cautions, "In reality, inflation may not occur in warped throats, even though the picture looks quite compelling."

In the end, the ultimate correctness of such models may not be their most important feature. "These models are based on geometries coming out of string theory for which we can make detailed predictions that we can then go out and test," says Bean. "In other words, they're a way of making a start."

Does anti

Matter edged out antimatter to make possible the universe we know. But no one yet knows how.

/// **BY RAY JAYAWARDHANA**

Astronomers often muse about the vast emptiness of the cosmos. Of course, the universe contains lots of matter — galaxies, stars, planets, and people. But this rather obvious statement belies one of the deepest cosmic mysteries: Why does matter exist at all? Why isn't the universe just a sea of radiation?

Scientists think the universe just after the Big Bang was so full of energy that subatomic particles — and their antimatter equivalents — briefly popped into existence. When a particle of matter (such as an electron), runs into its antiparticle (a positron), they annihilate each other in a burst of radiation. But the early cosmos was so dense — and the matter-antimatter particle pairs packed so tightly — that the particles should have quickly annihilated one another, leaving only radiation.

Because that's not the case, scientists think there must have been a slight preponderance of matter over antimatter. Physicists have worked out the magnitude of this asymmetry: For every billion antiparticles, there must have been a billion-plus-one particles of matter. All things in the universe today — including us — owe their existence to this seemingly insignificant matter excess.

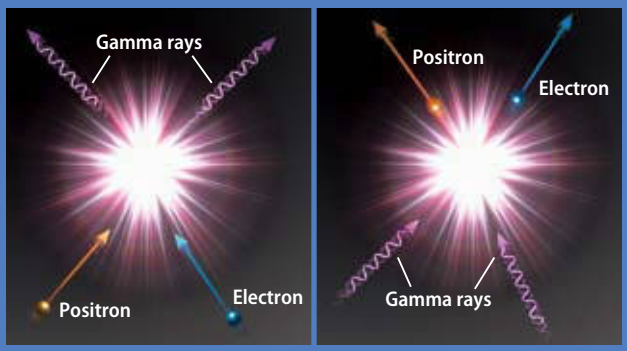
Contributing Editor **Ray Jayawardhana** *teaches astronomy and astrophysics at the University of Toronto.*

matter matter?

WHEN MATTER and antimatter particles collide, they annihilate one another in a gamma-ray flash. NASA's Compton Gamma Ray Observatory found a vast region near the center of our galaxy emitting this process' characteristic radiation. Part of the structure is a jet that blasts hot gas and antimatter out of the galaxy's plane.

ADOLF SCHALLER FOR *ASTRONOMY*

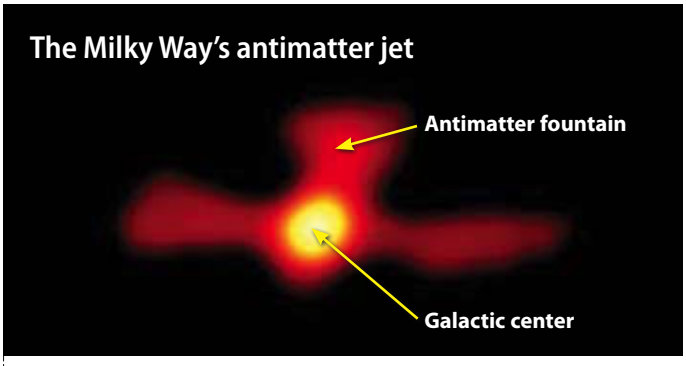
Producing and annihilating pairs



ASTRONOMY: ROEN KELLY

THE EQUIVALENCE of matter and energy means that each can take on the identity of the other. The collision of electrons and positrons produces a pair of gamma rays. Likewise, colliding gamma-ray photons can make electrons and positrons.

The Milky Way's antimatter jet



NASA'S Compton Gamma Ray Observatory detected gamma rays produced by electron-positron annihilation in the Milky Way's heart. The galactic center, thought to contain a supermassive black hole, is the bright central region. It lies within a 4,000-light-year-wide cloud of emission in the galaxy's plane. What astonished researchers was a faint lobe of emission rising out of the plane. The lobe is a jet of hot gas and antimatter 3,500 light-years long. NASA/W. PURCELL ET AL.

How that excess came about is among the most fundamental yet elusive questions in particle physics. The standard model of particle physics is remarkably successful at explaining the world around us in terms of a mere dozen fundamental particles — plus their antimatter doppelgängers. The model explains their various interactions through the exchange of "force carrying" particles like photons. Countless experiments have verified the model's predictions to amazing precision. Yet, the standard model's inability to explain why the universe so clearly favors matter over antimatter has remained a stubborn thorn in its side.

"It could be that this asymmetry really points to something beyond the standard model," says Edward "Rocky" Kolb of Fermi National Accelerator Laboratory (Fermilab) in Batavia, Illinois. "That's why particle physicists are so interested in this problem."

Antimatter's story

In 1928, a young British physicist named Paul Dirac combined special relativity and the newly developed theory of quantum mechanics into a mathematical equation describing an electron's behavior. His equation implied that for every particle, there's a corresponding antiparticle — a sort of mirror image having the same mass but opposite in all other respects, such as spin or electric charge.

Just 4 years later, Carl Anderson of the California Institute of Technology noticed a track left by "something positively charged, and with the same mass as an electron" while studying cosmic rays. After about a year of investigations, he decided these new particles were antielectrons, which he called positrons. Dirac was awarded a Nobel Prize in 1933 for his theoretical prediction, and Anderson received one 3 years later for his experimental discovery.

The antiproton and antineutron were identified in the 1950s in a particle accelerator named the Bevatron in Berkeley, California. Two independent groups observed the first antinucleus, made of an antiproton and antineutron, in 1965.

But it wasn't until 30 years later that scientists produced the first antiatoms, with a positron orbiting an antinucleus. In 1995, a team of physicists built up nine "antihydrogen" atoms at the European Organization for Nuclear Research, better known as CERN, near Geneva. Today, efforts continue at CERN to make large quantities of antihydrogen. The trick is storing the antiatoms long enough that scientists can study their behavior.

Breaking the rules

Since the 1960s, scientists have puzzled over the prevalence of matter in the universe because it suggests the breaking of symmetry at a fundamental level. The idea of symmetry is central to physics. In 1915, German mathematician Emmy Noether proved that symmetry implies a conservation law and vice versa.

For example, if a decaying muon emits an electron to the right, then an anti-muon should emit the electron to the left. This property is known as parity (or handedness). It should be conserved in particle interactions, along with other quantities such as charge.

However, the standard model allows

Discovering antimatter

AIP EMILIO SEGRÈ VISUAL ARCHIVES

1928
Paul Dirac combines quantum theory and special relativity into an equation for electrons that implies antiparticles exist.

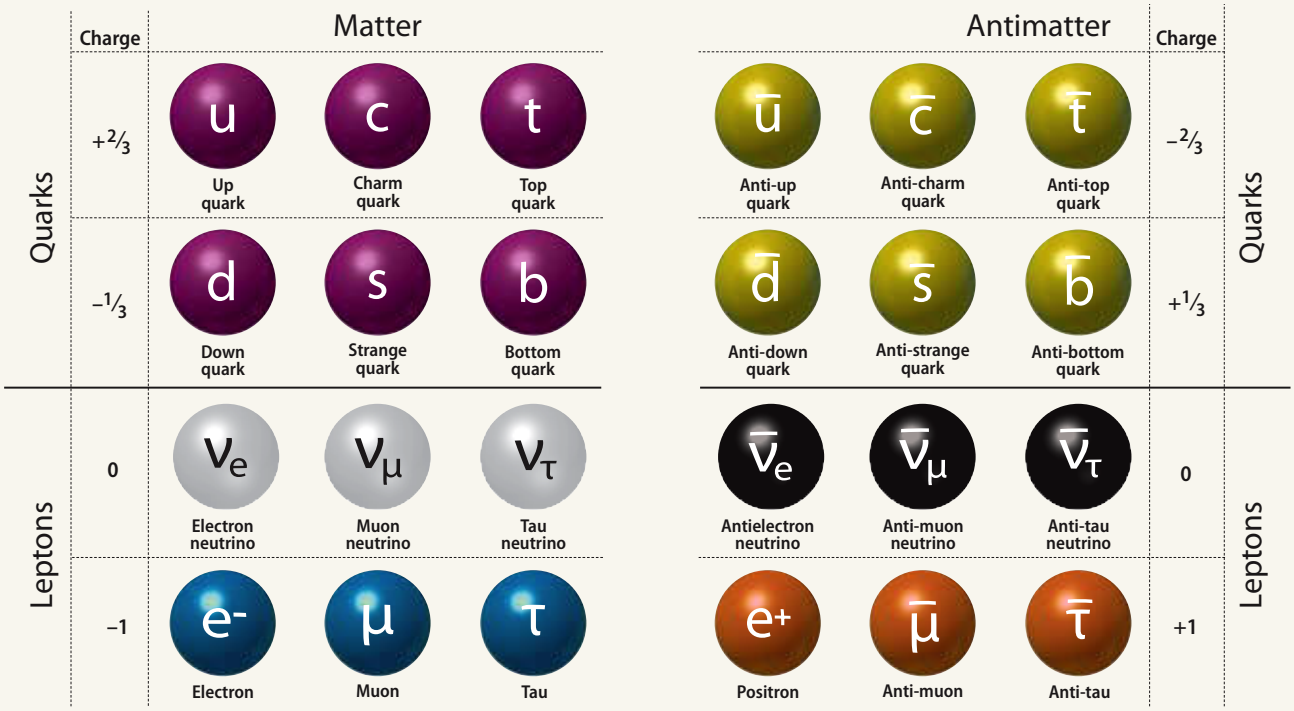
1932
Carl Anderson detects positrons from cosmic-ray showers in cloud chamber experiments. AIP EMILIO SEGRÈ VISUAL ARCHIVES

1933
Dirac wins Nobel Prize in physics.

1936
Anderson wins Nobel Prize in physics. Both he and Dirac won the prize at the age of 31. They tie as the second-youngest Nobel laureates.

1955
Emilio Segrè (right) and Owen Chamberlain discover antiprotons using the Bevatron at the University of California, Berkeley. AIP EMILIO SEGRÈ VISUAL ARCHIVES

A visit to the particle zoo



ALL MATTER is made up of atoms, which, in turn, contain baryons and leptons. Baryons, such as protons and neutrons, are made up of even smaller particles called quarks. Quarks come in six flavors and stick together by the strong nuclear force. Leptons, such as electrons and neutrinos, are fundamental particles. Each quark and lepton has an antimatter twin, with the same mass but opposite charge and magnetic spin. For example, an electron and a positron have the same mass, but one has a charge of –1 while the other has a +1 charge. Just as quarks combine to make baryons, antiquarks form antibaryons. *ASTRONOMY:* ROEN KELLY

these symmetries to break down occasionally, in a phenomenon called the charge-parity, or CP, violation. So, once in a while, an anti-muon decays by launching an electron to the right.

In 1964, a team of physicists working at the Brookhaven National Laboratory on Long Island, New York, first observed CP violation during the decay of electrically neutral particles called kaons. But, the effect was tiny — nowhere near enough to account for matter's dominance over antimatter. Since then, physicists have been searching for other instances of CP violation that might boost the numbers.

Two of the most sensitive experiments — one named BaBar at the Stanford Linear Accelerator in California and another called Belle at the High Energy Physics Laboratory in Japan — started operations in 1999. These "B factories" smash together electrons and positrons at nearly light-speed to create a shower of neutral particles known as B mesons, which disintegrate in a trillionth of a second into a variety of other exotic species. By recording hundreds of millions of such decays, physicists measured a 13 percent asymmetry in the decay rates of B mesons compared to those of anti-B mesons. This B/anti-B asymmetry is the most severe case of CP violation yet seen.

1956

Bruce Cork (standing, center) at California's Lawrence Berkeley National Laboratory leads a team using the Bevatron that discovers antineutrons. All three constituents of the atom have an antiparticle. AIP EMILIO SEGRÈ VISUAL ARCHIVES

Tsung Dao Lee (Institute for Advanced Study, Princeton) and Chen Ning Yang (Columbia University) conclude that weak interactions, like radioactive beta decay, break parity symmetry.

1957

Chien-Shiung Wu (Columbia University) shows that decaying cobalt-60 nuclei emit more electrons in one direction than another, violating parity symmetry.

Lee and Yang share the Nobel Prize in physics.

1959

Segrè and Chamberlain share the Nobel Prize in physics.

Excited faculty shared the news with students through the chalkboard message above. BERKELEY LAB LIBRARY

1964

James Cronin (University of Chicago) and Val Fitch (Princeton) show decaying K-mesons violate CP (charge-parity) symmetry.

ANTI-SPEAK

BELLE
An experiment at Japan's High Energy Physics Laboratory in Tsukuba. It's looking for symmetry violations in B mesons and their antiparticles.

COSMIC RAYS
High-energy particles, either atomic nuclei or electrons, that originate from the Sun and from sources beyond the solar system, such as supernova remnants.

CP SYMMETRY
Charge-parity symmetry. Most elementary particle interactions occur in the same way when the particles' electric charge or spatial coordinates are swapped.

NOvA
NOvA stands for NuMI Off-axis ν_e (electron neutrino) Appearance experiment. Located in Minnesota, the new detector will look for neutrinos beamed to it from Fermilab in Illinois.

PAIR PRODUCTION
The process by which an electron and a positron result from the collision of two gamma-ray photons or, more commonly in the laboratory, a single interaction with an atomic nucleus.

POSITRON
A positively charged particle with the same mass as the negatively charged electron; the antielectron, discovered in 1932.

AIP EMILIO SEGRÈ VISUAL ARCHIVES

WHERE IS ANTIMATTER?

Among energetic particles called cosmic rays, which originate from the far reaches of the Milky Way and bombard Earth every day, protons outnumber antiprotons 10,000 to 1. This suggests there isn't much antimatter in our vicinity of the galaxy.

One exception is the galactic center, where for decades astronomers have recorded gamma-ray emission caused by matter-antimatter annihilation. But astronomers don't see vast regions like this in the far universe, so it seems unlikely antimatter galaxies — or even large clouds of antihydrogen — exist.

How rare is this stuff? In 1998, a 4-ton instrument called the Alpha Magnetic Spectrometer (AMS-01) flew aboard space shuttle Discovery to look for antihelium nuclei among cosmic rays. The device's huge superconducting magnet and six sensitive detectors captured millions of helium nuclei, but none of their antimatter twins.

AMS COLLABORATION

AMS-02 will look for antimatter from the International Space Station.

A more advanced version of this instrument (AMS-02) is slated for launch to the International Space Station in 2010, where it will look for antimatter for 3 years. — *R. J.*

Unfortunately, that's still far from sufficient to account for the universe's matter-antimatter asymmetry. So, the search continues. One of the five major experiments to be carried out with CERN's Large Hadron Collider (LHC) — switched on for the first time in 2008 — is expected to look for additional sources of CP violation. The LHC is the world's most powerful particle accelerator. It occupies a circular tunnel some 16.8 miles long (27 kilometers) near the Swiss-French border.

Meanwhile, theorists have dreamt up several other ways to generate a stronger asymmetry. Some of these are rather complicated, if not downright contrived. Fermilab's Kolb describes the more outlandish suggestions as "constructing a grand edifice to explain this single number."

One idea is that the evaporation of primordial black holes, formed in the infant universe, did not conserve symmetry. Another explanation that looks more promising — thus, a current favorite — is that the asymmetry originates in the class of particles known as leptons, which includes the electron and the ghostlike neutrino.

Enter the neutrino

Austrian theoretical physicist Wolfgang Pauli, a giant in the development of quantum mechanics, first invoked neutrinos in 1930 as a "desperate remedy" to account for missing energy in a nuclear disintegration process known as beta decay. In beta decay, a neutron breaks into a proton and an electron (plus something else that flees the scene and carries some energy with it).

Pauli proposed the neutrino to explain the missing energy. These uncharged particles rarely interact with matter, making it rather difficult to pinpoint their characteristics. Tens of trillions of neutrinos, most of them produced in nuclear reactions in the Sun's core, pass through our bodies every second without leaving a trace.

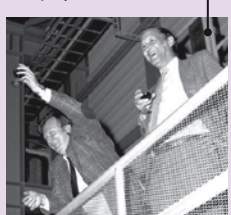
In fact, scientists didn't detect neutrinos experimentally until 1956, a quarter of a

1965
Two teams of physicists, one led by Antonino Zichichi (CERN) and the other by Leon Lederman (above) of Brookhaven National Laboratory in New York, simultaneously make an antideuteron (an antiproton bound to an antineutron).

1980
Cronin and Fitch win the Nobel Prize in physics.

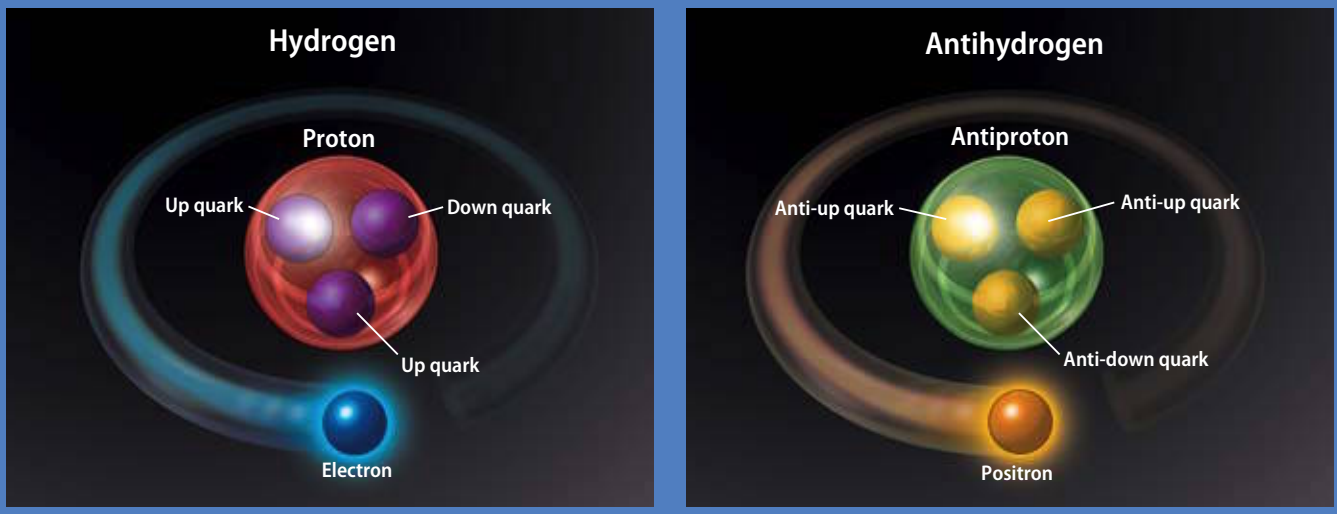
1980s
CERN's Simon van der Meer invents a method to control antiproton beams. Using the resulting proton/antiproton collider at CERN (shown above), Carlo Rubbia discovers the W and Z bosons, carriers of the weak force. CERN

1984
Rubbia (left) and van der Meer share the Nobel Prize in physics. CERN



1995
At CERN, the PS210 experiment led by Walter Oelert and Mario Macri produces nine hot antihydrogen atoms.

Hydrogen versus antihydrogen



ASTRONOMY: ROEN KELLY

TAKE TWO up quarks and a down quark, which together form a proton, then add an orbiting electron, and you have a hydrogen atom. To make antihydrogen, scientists combine two anti-up quarks, an anti-down quark, and an orbiting positron.

century after Pauli's prediction. Physicists once considered neutrinos to be massless, but now scientists agree neutrinos have some, albeit small, mass.

Data collected at vast underground detectors — at SuperKamiokande in Japan and Sudbury Neutrino Observatory in Canada — have shown that neutrinos, which come in three "flavors," can change from one type to another. Such oscillations can happen only if neutrinos have mass, although scientists have not measured the exact mass of these shifty particles yet.

Some physicists think the early universe was filled with super-heavy counterparts to the lightweight neutrinos that we observe today. When these heavyweight neutrinos decayed, they may have had a slightly higher probability of making matter rather than antimatter. Unfortunately, no accelerator has sufficient energy to create these hefty particles, so scientists have to infer whether this could have been the case by carefully observing the properties of the super-heavy neutrinos' lighter cousins.

In the late 1930s, a reclusive Italian physicist named Ettore Majorna suggested all neutrinos could have a strange property. While most elementary particles have a corresponding antimatter particle, usually with opposite charge and spin, neutrinos could be their own antiparticles. If he is right, two neutrons can undergo beta decay together so that the antineutrino emitted by one is immediately absorbed by the other. The net result is two neutrons disintegrating simultaneously without releasing any antineutrinos. Physicists call this hypothetical process "neutrino-less double beta decay." Of course, it would be rare, but observing it could be the key to unlocking the mystery of the matter-antimatter asymmetry.

If Majorna turns out to be right and neutrinos and antineutrinos are equivalent, super-heavy neutrinos in the newborn universe could have violated CP symmetry enough to tip the balance in favor of matter. A number of sophisticated particle physics experiments are already underway — in France, Italy, Switzerland, and elsewhere — to search for neutrino-less double beta decay. No definitive signal has turned up yet.

Physicists plan several more sensitive experiments. One of them, called NOvA, will consist of a giant tank filled with 24,000 tons of scintillator oil in northern Minnesota. The mineral oil-based fluid will detect neutrinos beamed through Earth from Fermilab some 500 miles (800 km) away. Once NOvA is completed in the next decade, scientists hope that it, and experiments like it, will be able to see a possible asymmetry in the way the three types of lightweight neutrinos morph into one another.

Physicists want to get to the heart of why the early universe so favored matter. To do so, they're building complex experiments that collect and study antimatter or peer into rare rule-breaking interactions. Sooner or later, these experiments will help scientists unravel one of the cosmos' most fundamental mysteries — why matter exists at all.

1997

Astronomers discover the Milky Way's "antimatter fountain." NASA/W. PURCELL ET AL.

1999

CERN activates its Antiproton Decelerator (AD), a first step in slowing and cooling antihydrogen so it can be studied. CERN

2002-2003

In 2002, the ATHENA experiment at CERN produces 50,000 cold antihydrogen atoms. In 2003, ATHENA's antihydrogen production exceeds 2 million atoms. CERN

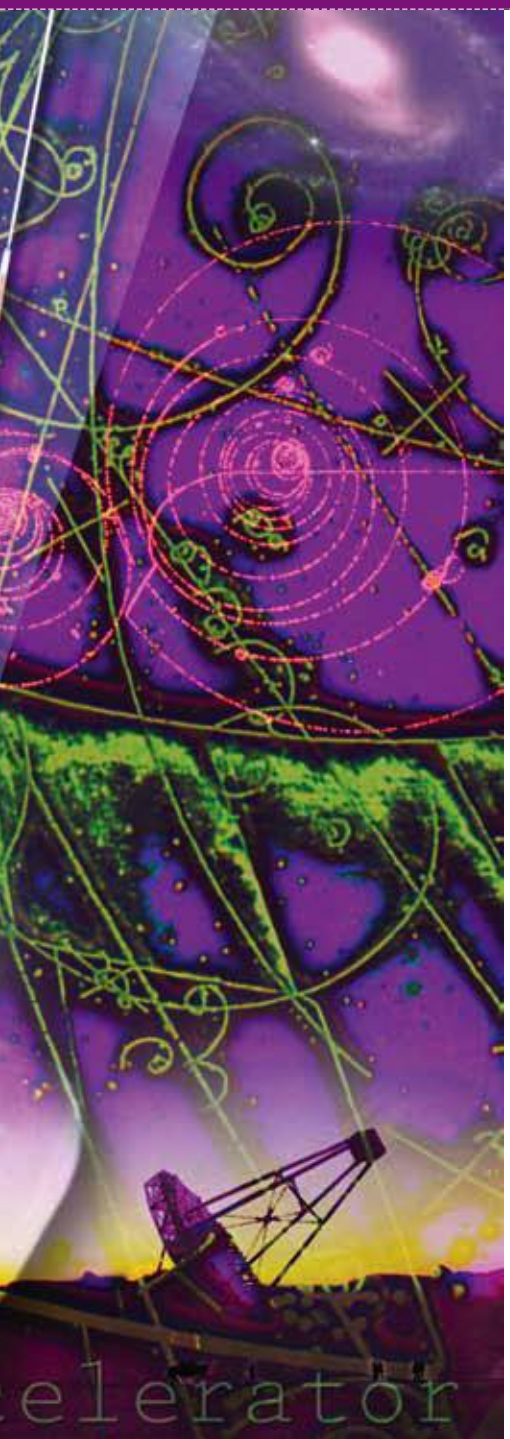
2004-2005

ATHENA experiment ends. In 2005, the Antihydrogen Laser Physics Apparatus (ALPHA) experiment starts up with improved technology for trapping antihydrogen atoms.

Don't ignore the

The highest-energy particles may hold answers to questions about the universe's most energetic phenomena. /// BY SCOTT WAKELY

universe's smallest details



Scientists use sophisticated instruments aboard balloons and satellites and on Earth's surface — from Antarctica to Argentina to Arizona — to study energy levels not in existence since moments after the Big Bang. Whether looking at the highest-energy gamma rays above the atmosphere or visible light on Earth's surface, researchers use different methods to answer one of the oldest riddles in astrophysics: Where in the universe do the highest-energy photons and subatomic particles come from?

This field, called particle astrophysics, merges the tiny world of particle physics with the large scales of astronomy. Studies in particle astrophysics are helping scientists understand the universe's earliest moments and most energetic events.

While astronomers use high-redshift (distant) objects to probe conditions in the early universe, particle physicists use ground-based accelerators. By colliding particles of ever-higher energies, physicists are able to produce, for brief instants, energy densities similar to those in the early universe. At these energies, the laws of nature streamline, simplify, and begin to reveal underlying symmetries. The higher the energies, the more fundamental the physics gets, and the closer to the Big Bang scientists probe.

Particle physicists have developed a sophisticated set of tools for measuring high-energy particles. With them, the researchers produced the so-called standard model. The model describes virtually all of the particles and interactions we are aware of in nature, but it is incomplete.

Questions lurk at the highest energies — energies that are far beyond our ability to recreate on Earth. And so particle astrophysicists look to the sky, to nature's own accelerators, to provide the energies needed to take the next step toward solving these cosmic mysteries.

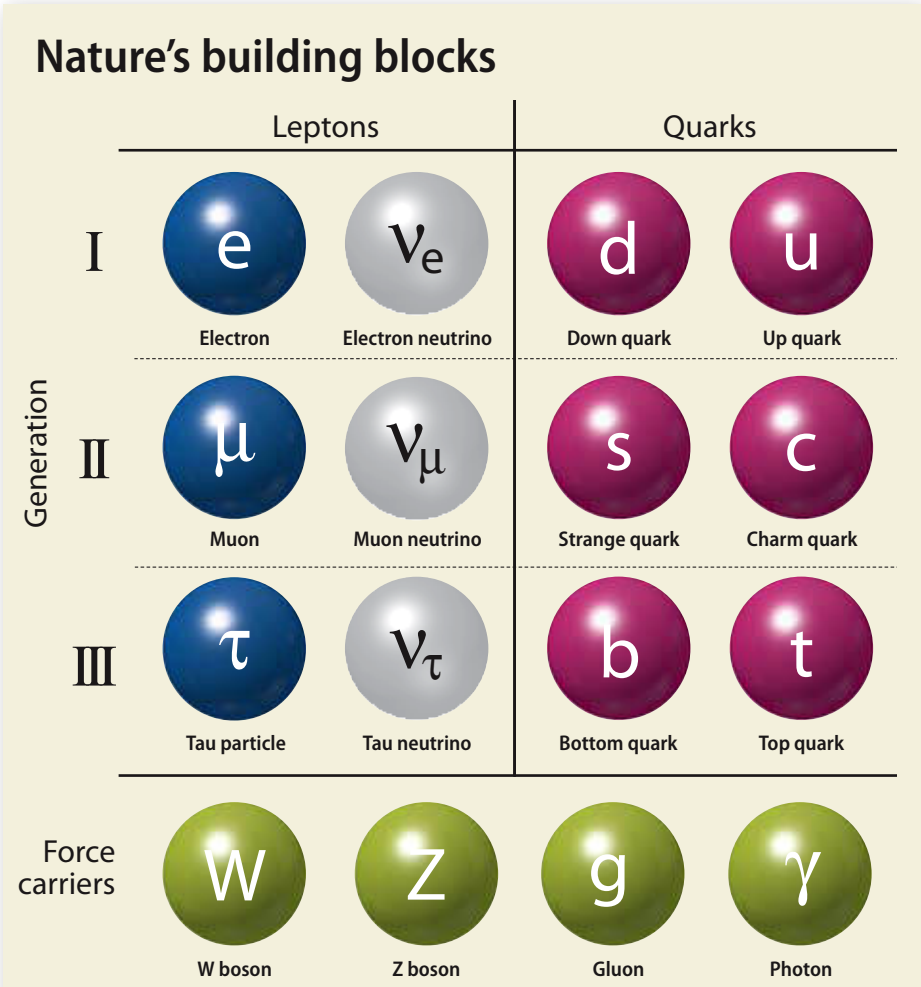
A disappearing charge mystery

Science historians can trace the birth of particle physics to Europe in the middle of the 19th century. For years, physicists struggled with a riddle: Why did electroscopes (sensitive instruments designed to detect and measure electrical charge) slowly lose their charge?

Scientists knew radiation energetic enough to strip electrons off (ionize) atoms could cause this effect, yet no one had isolated the source of radiation. Was it from radioactivity in natural sources within Earth (as many thought), or did it originate somewhere else? It was a vexing problem because it occurred even in electroscopes heavily shielded by lead.

HIGH-ENERGY ASTROPHYSICS is an exciting field that links the tiny with the immense. Advances in this area have helped scientists study the universe's earliest moments and its most energetic phenomena — and the next few years promise researchers more discoveries.

ASTRONOMY: KELLIE JAEGER; TELESCOPE ARRAY: VERITAS COLLABORATION; GALAXY: NOAO; BALLOONS: NASA/U. MARYLAND COSMIC RAY PHYSICS LABORATORY, AND TRACER/U. CHICAGO; PARTICLE TRACKS: CERN, FERMILAB, AND BROOKHAVEN NATIONAL LAB



THE STANDARD MODEL summarizes the rules of particle physics. All matter we can see and touch comprises combinations of leptons and quarks. Generation I particles are stable (and were the first group discovered), whereas generations II and III decay. Particles interact by exchanging bosons, the force carriers. These force carriers regulate the strong, weak, and electromagnetic forces, but maybe not gravity. Scientists don't yet have a complete gravitational theory that works at all scales. *ASTRONOMY:* ROEN KELLY

Enter Victor Hess, an intrepid young Austrian physicist from the University of Vienna who tested the ground-based radioactivity hypothesis. Hess took several balloon flights between 1911 and 1913 to measure the rate of electroscope discharge at different altitudes. If the ground was the culprit, then the discharge should have diminished as he climbed.

Hess flew as high as 17,000 feet (5,200 meters) — without oxygen equipment. After 10 ascents, he concluded the ionizing radiation initially decreased as his instruments climbed. However, in an unexpected twist, he also found that after this initial drop-off, the ionization rose again — doubling in intensity by 16,000 feet (4,900m).

Hess concluded that the results indicated "the penetration of the Earth's atmosphere from outer space by hitherto unknown radiation of exceptionally high penetrating capacity." In other words, the radiation wasn't from the ground — it wasn't even terrestrial. It was cosmic!

The birth of particle physics

Although he didn't know it at the time, Hess had discovered a steady and abundant stream of high-energy extraterrestrial particles impinging on, and interacting with, Earth's atmosphere. The stream — called the cosmic-ray flux — contains atomic nuclei, electrons, positrons, high-energy photons, and more. These cosmic rays were an entirely new source of ionizing radiation. Their discovery precipitated, in the words of Massachusetts Institute of Technology physicist Bruno Rossi, "one of the most extraordinary adventures in the history of science."

The discovery caught the scientific world unprepared. By 1911, the composition of the atom had scarcely been revealed. Nobel laureate Ernest Rutherford had just demonstrated that atoms have nuclei, and the entire taxonomy of subatomic particles comprised only the alpha (two protons and two neutrons — the helium nucleus), the beta (a high-energy electron or positron), and gamma rays. It took 25 more years for cosmic-ray physicists, who had been paying increased attention to the details of the cosmic-ray flux, to discover new particles.

The cosmic-ray flux became a laboratory for investigating fundamental physics: Scientists discovered the positron (the electron's antiparticle), the muon, and the pion. The excitement of these discoveries shifted the goal from trying to understand the origin of cosmic radiation to trying to understand its constituents. Enumerating the particles, and describing how they interact with each other, was the new adventure, and it produced the roots of what would become the standard model. Hess received the Nobel Prize in 1936 for his role.

After particle accelerators became common in the 1950s, particle physics as a science diverged from cosmic-ray physics. The accelerator labs could control and monitor particle collisions — particle physicists no longer needed cosmic rays.

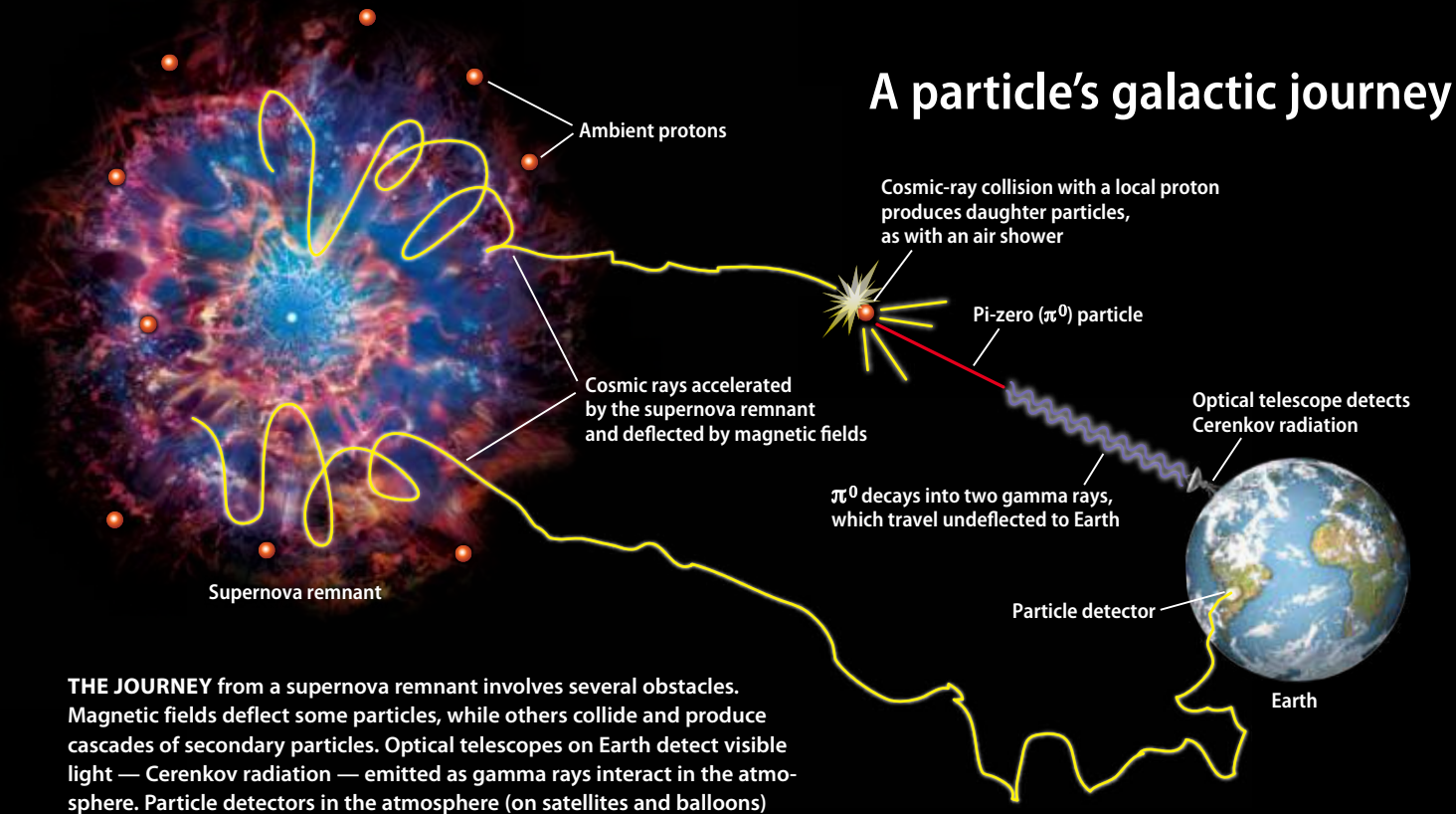
Cosmic rays don't point

Nearly 100 years after Hess' discovery, scientists still do not understand many things about cosmic rays. The exact nature and origin of cosmic rays remain among the longest-standing mysteries in astrophysics.

In addition to possibly having an impact on Earth's weather and climate patterns, cosmic rays fill the galaxy with an energy density equivalent to that of starlight, turbulent gas motion, and even the cosmic microwave background radiation. We can't claim to understand our galaxy if we don't understand cosmic rays.

Cosmic rays contain, more or less, the same ratio of elements we see in our solar system, and they possess energies from around 100 million (10^8) electron volts (eV)

Scott Wakely *is an assistant professor of physics at the University of Chicago. His research involves balloon-borne cosmic-ray instruments, ground-based gamma-ray telescopes, and other detectors.*


A particle's galactic journey
Ambient protons
Cosmic-ray collision with a local proton produces daughter particles, as with an air shower
Pi-zero (π^0) particle
Cosmic rays accelerated by the supernova remnant and deflected by magnetic fields
Optical telescope detects Cerenkov radiation
π^0 decays into two gamma rays, which travel undeflected to Earth
Supernova remnant
Particle detector
Earth

THE JOURNEY from a supernova remnant involves several obstacles. Magnetic fields deflect some particles, while others collide and produce cascades of secondary particles. Optical telescopes on Earth detect visible light — Cerenkov radiation — emitted as gamma rays interact in the atmosphere. Particle detectors in the atmosphere (on satellites and balloons) and on the surface detect higher-energy cosmic rays. *ASTRONOMY:* ROEN KELLY

to more than 100 billion billion (10^{20}) eV. But what is their source?

We can't just collect cosmic rays and trace their trajectories to see where they originate. Most cosmic rays are charged particles; therefore, they are buffeted and deflected as they travel through large-scale magnetic fields. Even in our galaxy's weak magnetic field (roughly 100,000 times weaker than Earth's), a typical cosmic ray's direction is randomized after traveling a few light-years. Only the highest-energy particles can preserve their direction.

In November 2007, scientists at the Pierre Auger Cosmic Ray Observatory in Argentina announced that the most likely candidates for the source of the highest-energy cosmic rays are active galactic nuclei powered by supermassive black holes.

Supernova connections

Scientists must look for less direct clues to cosmic-ray origins. One method concerns the "power budget" of cosmic rays. Scientists add up the kinetic energy of all of the cosmic rays in the galaxy and then figure out the amount of power it would take to produce them. This is some 10^{42} ergs per second — about 10^{29} megawatts, or a billion times the Sun's total power output. Probably only one event in the galaxy can impart this much power to particles: a supernova.

A supernova's expanding shell of debris can sweep up charged particles and accelerate them to high energies. Only a few supernovae per century would provide the power to generate all of the galaxy's cosmic rays. Furthermore, theoretical models of this acceleration process recreate features scientists have measured in the cosmic-ray flux. Using X-ray satellites, astronomers observe synchrotron emission (radiation emitted when high-energy electrons travel along trajectories in magnetic fields) in some supernova remnants (SNRs); this indicates large numbers of very energetic electrons there. So high-energy electrons, at least, can be made in SNRs. What about nuclei, which make up the bulk of cosmic rays?

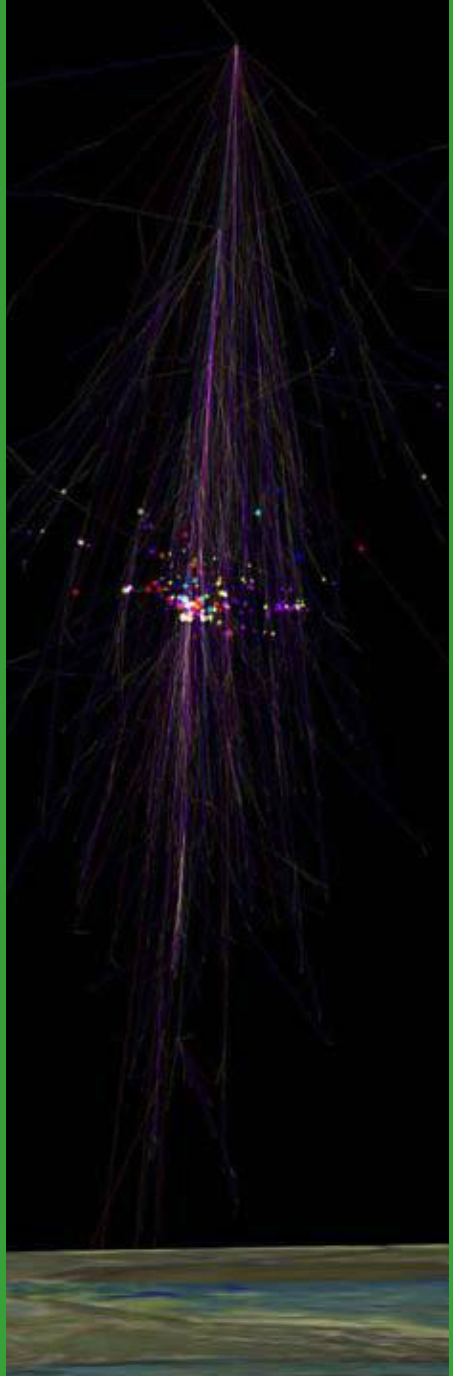
WE CAN'T CLAIM to understand our galaxy if we don't understand cosmic rays.

The case for them is purely circumstantial. Scientists are searching for clues to how these cosmic rays evolve as a function of energy. For instance, if their composition changes as energy increases, could this point to a specific model of supernova origins?

To answer this question, researchers measure cosmic rays' properties, such as energy and charge. Unfortunately, the number of cosmic rays rapidly dwindles as their energy increases. For every factor-of-10 increase in energy, the number of cosmic rays drops by a factor of 50 to 100 — requiring instruments 50 to 100 times larger.

This wouldn't be a problem if cosmic-ray research could be performed from the ground, but it can't. Earth's atmosphere is an effective shield, preventing primary cosmic rays from reaching the surface. Instead, they are attenuated and absorbed through violent collisions with air nuclei. This leads to cascades of daughter particles called air showers. Hess' discovery, and the subsequent development of particle physics, was based not on the direct detection of cosmic rays, but on the observation of these air showers.

To limit the atmosphere's interference, the most sensitive instruments for measuring cosmic rays are on high-altitude balloons or spacecraft. One of these detectors is the University of Chicago's balloon-borne Transition Radiation Array for Cosmic Energetic Radiation (TRACER) instrument, which, in December 2003, completed a 14-day flight around the South Pole, cruising at roughly 125,000 feet (38,000m).



PARTICLES FROM SPACE

Cosmic rays bombard Earth at a rate of about one particle per square centimeter per second. Primary cosmic rays are 90 percent protons, with electrons, heavier nuclei, and gamma-ray photons making up the rest. Cosmic rays move fast, with velocities near or at the speed of light (any object with mass can't reach light-speed). Therefore, they have high energies ranging from a billion (10^9) to 100 billion billion (10^{20}) eV.

When primary cosmic rays collide with atoms in the atmosphere, the result is a shower of particles — called secondary, or daughter, particles. The initial secondaries are mostly pi-mesons — neutral and charged pions (π^0,π^+, π^-). Neutral pions decay into pairs of gamma rays, which may create an electron (e^-) and a positron (e^+). The charged pions eventually decay into muons (μ) and muon neutrinos (ν_μ). As a result, a large number of electrons, positrons, and muons hit Earth's surface.

Scientists use optical telescopes and pure-water tanks on the surface to detect Cerenkov light emitted when gamma rays and other high-energy particles traverse the atmosphere. They also use detectors on balloons to study these particles in the atmosphere. — *Liz Kruesi*

INCOMING COSMIC RAYS — an alpha particle in this simulation — collide with atoms in Earth's atmosphere, creating a shower of lower-energy particles. The alpha particle creates an array of particles and radiation above the Auger Observatory's Argentina site. Purple corresponds to gamma rays, red to muons, yellow to electrons and positrons, blue to protons, and cyan to neutrinos. COSMUS (UNIVERSITY OF CHICAGO: RANDY LANDSBERG, MARK SUBBARAO, AND DINOJ SURENDRAN)

TRACER uses lightweight detectors to maximize the cosmic-ray collecting area for the equipment's weight. Due to its great size, TRACER can make detailed measurements above energies of 100 trillion (10^{14}) eV, approaching the region where hints from supernova models might appear.

Cosmic tennis balls

At ultrahigh energies, above 10 billion billion (10^{19}) eV or so, the number of cosmic rays falls to less than 1 particle per 0.4 square mile (1 square kilometer) per year. These particles have energies equivalent to well-hit tennis balls; this vastly exceeds what scientists can achieve in the largest accelerator labs. In fact, these energies also outstrip any boost a supernova remnant can deliver — which makes their source more mysterious still.

Measurements are tricky, too, because even the largest balloon or space-based missions wouldn't collect enough particles to be useful. Instead, scientists must use the extensive air showers these particles produce. With a few relatively simple detectors distributed over a large area, scientists can measure multiple aspects of air showers with enough precision to reconstruct some of the properties of the original cosmic rays.

While not as accurate as direct instruments, these detectors can capture the rarest particles because of the large area the equipment covers. One such detector, the Pierre Auger Observatory, was completed in November 2008. Auger is the largest scientific instrument in the world. It covers more than 1,160 square miles (3,000 square kilometers) — roughly the size of Rhode Island — with 1,600 individual detectors each separated by 0.9 mile (1.5 km). Auger has tracked down, for the first time, extragalactic point sources of ultrahigh-energy particles. It also will explore other fundamental physics topics.

Supercharged photons

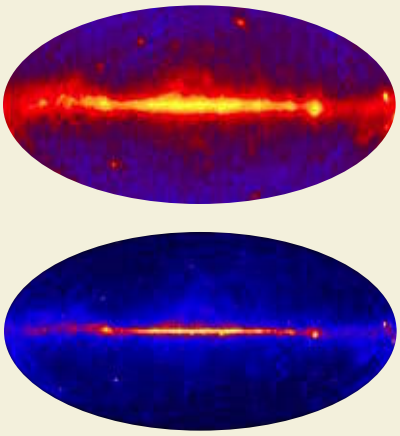
Although gamma rays are less than 1 percent of the total cosmic-ray flux, they have provided some of the most exciting discoveries in particle astrophysics during the past 15 years. Magnetic fields do not alter gamma rays' trajectories, and, therefore, scientists can trace the gamma rays back to their sources. Because the same exotic environments that generate high-energy charged particles can also produce gamma rays, researchers know what to look for when tracking cosmic-ray origins.

In the 1990s, scientists used the Energetic Gamma Ray Experiment Telescope (EGRET) aboard the Compton Gamma Ray Observatory to look at several supernova remnants in our galaxy. Scientists measured the flux of photons with energies of a billion (10^9) eV (or 1 GeV).

They found the flux is consistent, in several cases, with what you'd expect if cosmic rays were being produced in the region. This was an exciting but puzzling find because follow-up observations at higher energies found no emission.

In addition, EGRET — while constructing a map of the GeV sky — discovered an entirely new astronomical beast, the so-called gamma-ray blazar. These blazars are a form of active galactic nuclei, objects that researchers know are prolific producers of radiation at other wavelengths. What they didn't know (or even guess) was that blazars can also produce photons beyond 10^9 eV. More remarkable still is the fact that these objects, located hundreds of megaparsecs away, can outshine objects, such as supernovae, in our own galaxy.

EGRET identified more than 65 of these extragalactic gamma-ray emitters. The EGRET mission ended in 2000, but its legacy is continuing with the Fermi Gamma-ray Space Telescope — NASA's next gamma-ray satellite. Launched June 11,

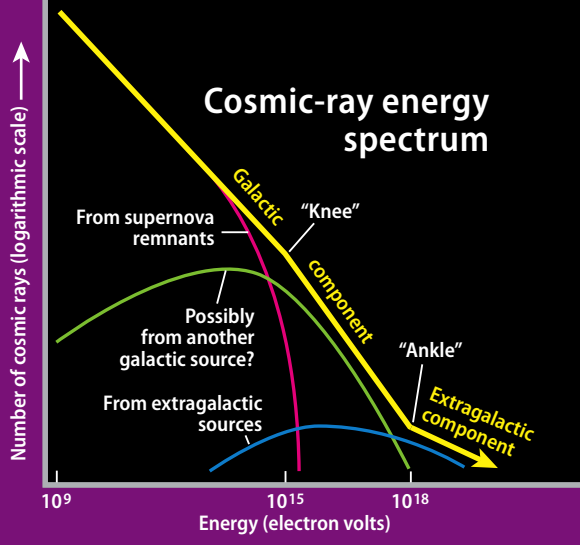


THE GAMMA-RAY SKY as seen by EGRET (top) revealed unknown high-energy sources. The bottom image is the first all-sky map from the Fermi Gamma-ray Space Telescope. TOP: EGRET TEAM/S. W. DIGEL (NASA/GSFC); BOTTOM: NASA/DOE/FERMI LAT COLLABORATION

WHAT'S THE SOURCE?

The cosmic-ray spectrum is an important tool in particle astrophysics. The yellow line here comes from data. As you look at higher energies, the number of detected cosmic rays drops, but, along the way, there are two kinks: The first is the "knee," and the second is the "ankle." Scientists want to know what causes these kinks.

Cosmic rays above the ankle are from galactic sources. The section above the knee shows cosmic rays created by supernova remnants. Below the ankle, at the highest energies, is the extragalactic component. The area between the knee and the ankle is a possible transition between cosmic rays accelerated by supernova remnants and another source. Scientists aren't sure what causes this kink, or even if it's produced by a different source. More data will answer these questions. — *L. K.*



ASTROPHYSICISTS have observed the energies shown in the yellow line. The three other lines show how suspected sources possibly contribute to the overall signature of cosmic rays. *ASTRONOMY:* ROEN KELLY

2008, Fermi is an order of magnitude larger and more accurate than EGRET.

In addition to the potential to discover thousands of new grazars, Fermi has a high sensitivity to large-scale annihilations of elementary particles. These particles, not yet seen in accelerator labs, include some of the dark-matter candidates fiercely pursued by scientists, as well as heavy relic particles that may have survived from the Big Bang.

Photons from the edge

As with charged cosmic rays, the frequency of gamma rays declines at higher energies, which makes them difficult to measure. Therefore, ground-based detectors are the only option for making measurements. Once again, Earth's atmosphere interferes by absorbing the original gamma rays and producing air showers.

In the course of these showers, tiny flashes of blue light are emitted. Large optical reflecting telescopes can collect this light — called Cerenkov radiation. The challenge is teasing out the gamma-ray signatures from the overwhelming background of charged-particle showers. In the late 1980s, the Harvard-Smithsonian Center for Astrophysics' Trevor Weekes pioneered a technique to achieve this. As a result, a new form of astronomy has emerged: very-high-energy (VHE) astronomy, which deals with the highest-energy photons known — energies between 10 billion (10^{10}) and 100 trillion (10^{14}) eV.

> THE SAME EXOTIC environments that generate high-energy particles can also produce gamma rays.

In 2005, the European collaboration running the High Energy Stereoscopic System (HESS) — named to honor Victor Hess — used Weekes' technique to perform the first high-sensitivity survey of the galactic plane in VHE gamma rays. Using four 12-meter optical reflectors in Namibia, they made a catalog of eight previously unknown gamma-ray sources — two of which hadn't been detected at any wavelength.

Before that discovery, in late 2004, HESS released the first 2-D image of VHE gamma-ray emission from a supernova remnant. The result was a definite gamma-ray signal with virtually all of the characteristics predicted from a cosmic-ray accelerator. Many heralded it as the clinching evidence that solved the mystery of cosmic-ray origins.

Three other VHE gamma-ray observatories are under construction. One effort, led by American, Canadian, Irish, and English scientists, came online in April 2007 in Arizona. This system, the Very Energetic Radiation Imaging Telescope Array System (VERITAS), is focusing the same level of sensitivity on the Northern Hemisphere that HESS focuses on the Southern.

New questions, new tools

Employing techniques perfected in accelerator labs, particle astrophysicists are using charged particles and gamma rays to explore the universe — while addressing fundamental questions. Even neutrino astronomy may be added as a specialty, with several massive installations currently under construction. As for the mystery of cosmic rays: Will the latest VHE gamma-ray results truly resolve this longstanding conundrum? Only time and more data will tell, which is all right. After 100 years, we've learned to be patient.

THE HESS TELESCOPE ARRAY in Namibia has been fully operational since September 2004. In just 2 years, HESS may have answered the cosmic-ray-origin question. HESS COLLABORATION

TO SIMULATE THE WARPING OF SPACE-TIME as two black holes merge, physicists had to convert relativity's complex equations into a form that supercomputers could run. For years, the computers just crashed. But researchers finally found a way to make it work.

ASTRONOMY: ROEN KELLY; PORTRAIT: OREN JACK TURNER/LIBRARY OF CONGRESS, PRINTS & PHOTOGRAPHS DIVISION

Scientists are colliding virtual black holes to verify the general theory of relativity. /// BY ADAM FRANK

Putting Einstein to the test

Simulating the merger of black holes is no small scientific feat. For one thing, it requires a lot of computing horsepower — the kind you can get only from a supercomputer. It also involves solving complex, multilayered equations of Einstein's theory of general relativity at lightning speed. Using supercomputers, researchers in the field of numerical relativity hope to shed light on the physics of the most violent events in the cosmos. Black hole mergers and colliding neutron stars are two primary candidates.

But numerical relativity demands that researchers take on Albert Einstein full bore. Solving the equations of general relativity — Einstein's grand theory of gravity — is a difficult enough problem. Their additional challenge is to digitally animate the most complex behaviors hiding inside those equations.

Getting results has become urgent. A new kind of telescope — gravitational wave detectors, built to sense ripples in the fabric of space and time — has recently come on line. These gravity observatories were built specifically to detect events like black-hole mergers. But the telescopes need guidance from computer models to know what sort of signal to look for. This special imperative has made numerical relativity the kind of challenge that draws theorists with a special kind of ambition.

For years, the computer codes at the heart of numerical relativity simulations could do little more than simply crash. All paths seemed blocked; nothing worked. In spite of all the intellectual firepower attracted to the research, and 30 years of work, some theorists were giving up hope. Simulating Einstein's universe might not just be hard — it might be impossible.

But recent breakthroughs in computer modeling by numerical relativists mean the simulations work. They found a way to run Einstein's equations as black holes collide, without crashing their supercomputers. Animations created from the model runs show black holes spiraling into each other and merging while emitting blasts of radiation and rippling gravity waves.

This research has opened a new window on the universe — one in which astronomers can hopefully observe disturbances in space-time as readily as flashes of X rays and visible light.

Adam Frank *is a professor of astrophysics at the University of Rochester in New York. His new book,* The Constant Fire: Beyond the Science vs. Religion Debate, *was published in January 2009 by the University of California Press.*

Listening for black holes

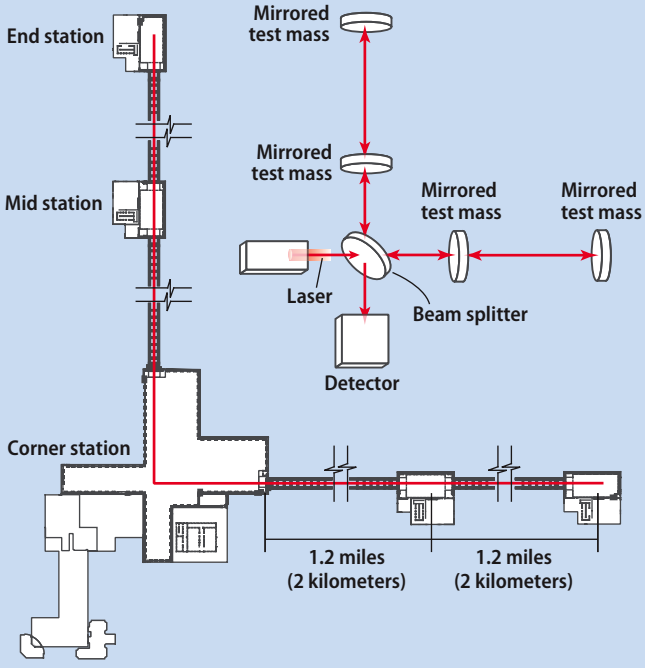
On the dusty plains of the Hanford Nuclear Reservation, about 200 miles (320 kilometers) southeast of Seattle stands numerical relativity's reason for existence. It consists of two long vacuum chambers that meet to form an L-shaped gravity observatory. The facility is called LIGO, the Laser Interferometer Gravitational-wave Observatory.

The LIGO Hanford Observatory, along with a sister facility, the LIGO Livingston Observatory in Louisiana, represents a new

WITHIN A CLOUD OF HOT GAS, radio-energy jets emanate from two supermassive black holes (the two bright spots) in the galaxy NGC 1128. Recent observations suggest the black holes will merge into one, radiating a cosmic earthquake of gravitational waves. X-RAY IMAGERY: NASA/CXC/AIFA/D. HUDSON & T. REIPRICH ET AL.; RADIO IMAGERY: NRAO/VLA/NRL

AT THE LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY (LIGO) site near Richland, Washington, astronomers search for space-time disturbances. A sister LIGO observatory operates in Livingston, Louisiana. Observations began in 2005. LIGO LABORATORY

Laser Interferometer Gravitational-wave Observatory (LIGO)



EACH OF THE LIGO DETECTORS sends laser pulses down two 2.5-mile (4 kilometers) arms and combines their light. This diagram shows the layout of the Hanford, Washington, observatory. By making laser light travel up and down the arms and interfere with itself, scientists will be able to deduce minute changes in the light's path from a gravity-wave encounter. *ASTRONOMY:* ROEN KELLY

kind of telescope. Engineers designed LIGO to pick up gravitational waves — ripples on the surface of space-time's ocean that are a key prediction of Einstein's general theory of relativity.

Wiggling any mass back and forth produces gravity waves that move across the fabric of space-time. Wiggling a massive, compact object like a black hole creates gravity waves so powerful that scientists hope instruments can detect them across astronomical distances.

"Gravity waves are the point of LIGO," says Scott A. Hughes, a professor of physics at MIT's Kavli Institute for Astrophysics and Space Research in Cambridge, Massachusetts. "The crossed lasers are designed to detect changes in space-time produced by passing gravity waves. But you have to know what to look for."

When people started thinking about LIGO, they realized that the merger of two black holes would produce a strong signal. A binary system of two massive stars orbiting each other sets the stage for the merger. When the stars go supernova, they each leave behind a black hole corpse.

The black holes remain locked in orbit around each other. The closer they get, the more they disturb the space-time in their vicinity. The system generates gravity waves that ripple outward. The waves sap orbital energy from the black holes, which then circle each other ever more closely. They eventually merge into a single object in a cataclysm of distorted space-time and radiating gravity waves.

"LIGO should be able to see these mergers," Hughes explains. The LIGO project set researchers on the black hole merger problem with a vengeance. For years, scientists have been trying to use general relativity to calculate the signals LIGO scientists should look for in their data. A match would mean LIGO has detected a black hole merger.

Death spiral

There are three phases to a black-hole merger. First, "inspiral" occurs as the black holes circle around each other on an ever-tightening orbit. Until they get close, slight modifications of Newtonian gravitational attraction work just fine.

At the middle phase of the merger, all hell breaks loose. Tracking two black holes as they spiral into collision demands the full-blown equations of general relativity with no tricks or simplifications. The merger also produces the strongest LIGO signal. The melding of two rapidly moving black holes shreds space-time and radiates a torrent of gravity waves from the scene.

Like the inspiral phase, the merger's conclusion is relatively easy to calculate. "You end up with a single black hole," says Hughes. "The event horizon of the merged black hole oscillates for awhile and radiates gravity waves until it stabilizes." This final phase of a black hole merger is called the ringdown.

Accurately reproducing the details of a merger and its gravity wave signature is the grand challenge needed to satisfy LIGO. Earlier this decade, a merger was the prize everyone was gunning for. Winning that prize meant Einstein's equations would have to be wrestled to the mat.

Einstein's impossible legacy

It's the complexity of relativity theory that makes numerical relativity so hard. To handle a problem like merging black holes, theorists have to solve 10 interwoven equations simultaneously. Take just a few steps into a calculation and you can end up with hundreds of terms — smaller pieces of equations — to follow. It's like doing algebra and calculus in the middle of a tornado.

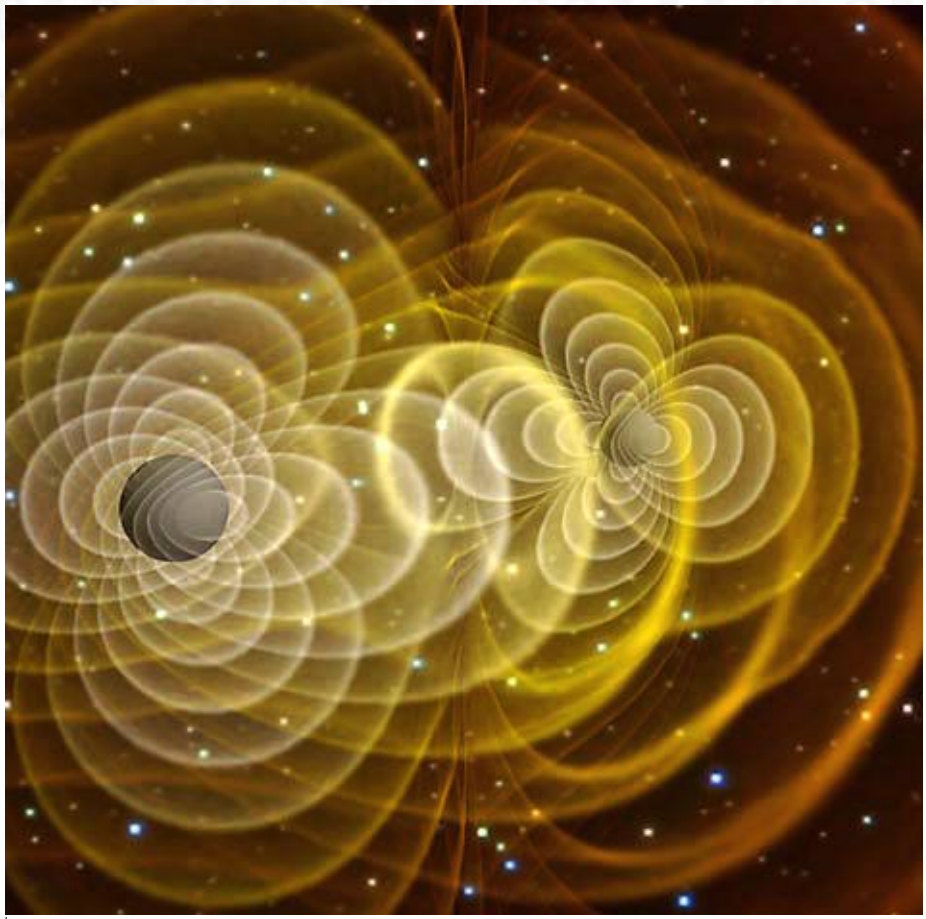
Theorists had to first think of ways to convert the equations of general relativity into a form that computers could swallow. "The first attempt at numerical relativity came in the 1970s," says Joan M. Centrella, chief of the gravitational astrophysics laboratory at Goddard Space Flight Center in Greenbelt, Maryland. "It was really a heroic effort."

Centrella understands such theoretical heroism. She and her research group have worked on numerical relativity simulations for 20 years. The first efforts focused on direct collisions of black holes. The calculations were crude, but they did point the way for a future generation of researchers. To make real progress, scientists would have to figure out how to simulate Einstein's 4-D space-time on a computer and make it work for the most complicated situations.

In general relativity, space and time are intrinsically mixed. All objects in space-time, including you and me, have four dimensions. Each of us occupies and moves through the three dimensions of space and, simultaneously, a fourth dimension of time. That means each person's life history is a four-dimensional object stretching from birth to death. The same principle applies to black holes.

Black hole weirdness

To make it possible to run the equations of general relativity in a computer, researchers had to develop a way to accommodate the complexities of four-dimensional objects. Then, they had to develop a way to visualize the data as 2-D and 3-D animations. This left another major challenge: simulating the black holes themselves.



THE INTENSE GRAVITY FIELDS of two black holes merge in a computer simulation performed by scientists at NASA's Goddard Space Flight Center in Greenbelt, Maryland. Astronomers hope to detect gravity waves emitted during black-hole mergers.

CHRISTOPHER HENZE/NASA AMES RESEARCH CENTER

Every black hole is surrounded by an event horizon, the point beyond which ordinary radiation cannot escape the object's powerful gravity. The event horizon is the boundary between our universe and the weirdness inside.

Anything passing through the event horizon exits our world forever. It's no surprise, then, that trying to simulate the interiors of black holes in computer simulations creates problems.

Inside of the event horizon is a place simulations can't go. Yet, without a way of representing black holes in the model, there could be no numerical relativity. Over the years, two strategies emerged to treat the problem. "You can either cut the

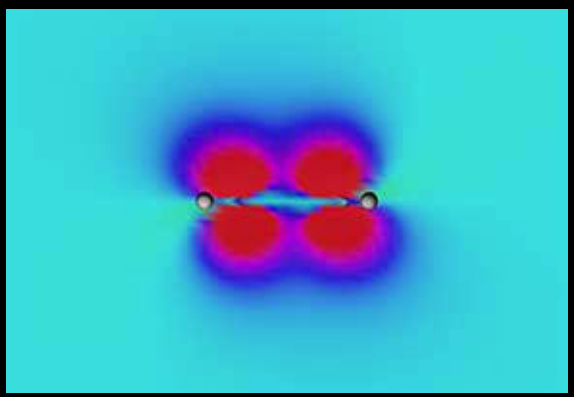
NASA'S COLUMBIA SUPERCOMPUTER is one of the fastest machines of its kind in the world. Tremendous processing power is required to calculate distortions in space-time caused by merging black holes.

TOM TROWER/NASA AMES RESEARCH CENTER

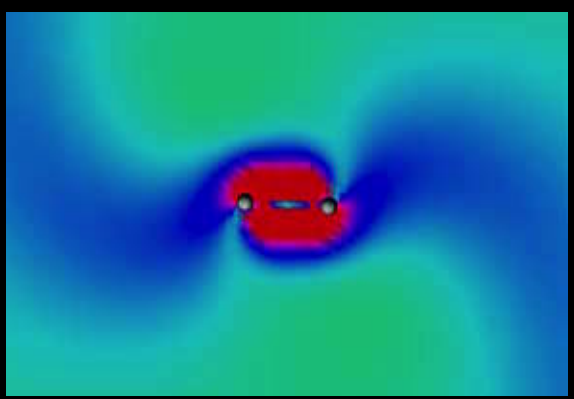
Wiggling a massive, compact object like a black hole creates gravity waves so powerful that scientists hope instruments can detect them across astronomical distances.

How black holes merge in a supercomputer

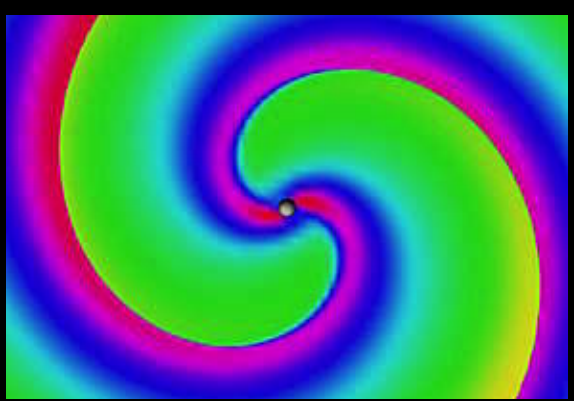
TO RECREATE THE MERGER OF TWO BLACK HOLES, numerical relativity researchers translate the equations of Einstein's general theory into a form a computer can understand and process. As the black holes circle each other, getting closer and closer, the computer model calculates their effect on local space-time. All images: Hans-Peter Bischoff/Center for Computational Relativity and Gravitation/Rochester Institute of Technology



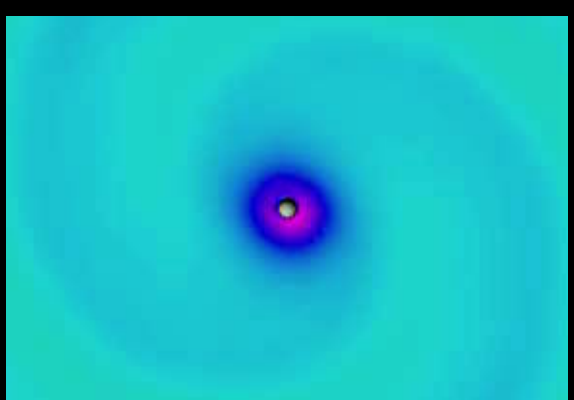
1 At this point, the black holes are still far apart, so the disturbance in the "fabric" of local space-time is minor. To merge, they will have to tighten their mutual orbits by shedding energy. This is the beginning of the "inspiral" phase of the merger.



2 As the black holes get closer, the interaction of their gravitational fields intensifies. The blue patterns at left and right indicate increasing disturbances in space-time called gravitational waves. They remove energy released during the merger.



3 The black holes have merged and the disturbance to space-time is at maximum. The spiral pattern means gravitational waves are radiating in all directions, carrying away energy shed by the black holes in their merger process.



4 A single black hole is born in the merger. Now, in the "ringdown" phase of the process, the black hole vibrates for a period of time as the system settles back into a stable state. The overall disturbance to space-time is minimal.

black holes out of the grid in a process called excising, or you can try and slow the evolution down near the hole and then insert a solution you already know, which is called puncture," explains physicist Manuela Campanelli, director of the Center for Computational Relativity and Gravitation at the Rochester Institute of Technology (RIT) in New York.

Each choice has its problems, and neither worked well. The difficulties of computational relativity brought the field to a standstill. Only a few years ago, the situation appeared to be getting desperate. "The codes just crashed and crashed and crashed," Centrella says. "You couldn't even get an entire orbit out of them."

The inherent mathematical nastiness of general relativity's equations and the sheer difficulty of translating them into computer code rendered the models wildly unstable. Just a few steps into a calculation, the machines locked up by trying to divide by zero or some other impossibility.

Campanelli remembers it as a dark time. "People had really lost hope," she says. "These were scientists who had spent years building their codes. All that work, all that mathematics. No one wanted to toss it away and start again."

Then, in the midst of the melancholy, everything changed. It was a day that numerical relativists are not likely to forget for a long time.

The lone gunman

On April 19, 2005, numerical relativists gathered at a conference center in the mountains of Banff, Alberta. Frans Pretorius, a professor of physics at Princeton University, showed up with a secret. "Frans was the classic lone gunman," Hughes says. "He appeared at a conference and said 'Watch this.' "

After describing the mathematical background of his numerical code, Pretorius showed the audience a simulation with five full orbits of a black-hole pair.

"It was just amazing," Hughes says. "Frans had solved it. He got it to work. It was like everybody was climbing this mountain only to find Frans on top already waving down at them."

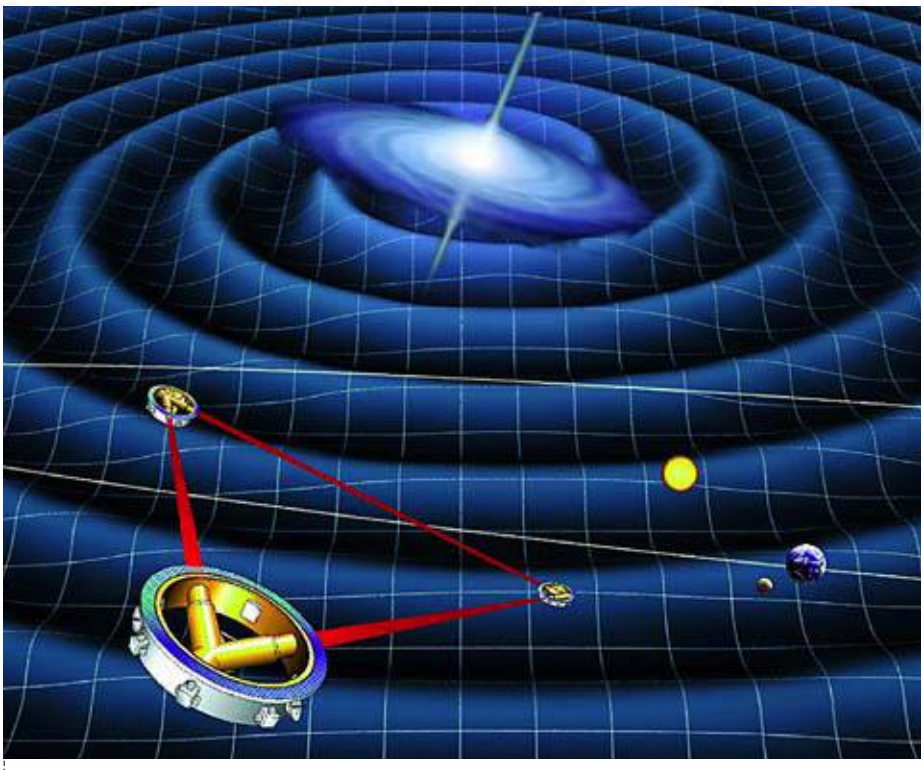
In Pretorius' new method, Einstein's equations take on a form similar to those describing simple waves. It was a highly abstract, nonintuitive approach. But progress was not immediate. "My first attempt

failed," he recalls. "In the second attempt, things were a little better."

News of Pretorius' achievement leaked out before his talk. The buzz had already started when he arrived at the conference hall. "People were text messaging during my talk," he recalls. "Some guy set up with a video camera on a tripod and aimed it right at me. It was kind of embarrassing."

After Pretorius showed his animations and finished his talk, the community tried to digest what it had just seen. A few people were hostile. "There was a lot of investment in the methods researchers had been working with," Pretorius says. "Not everyone was pleased that I had come at it in an entirely different way and succeeded."

But most of Pretorius' colleagues were thrilled. He had proved that numerical relativity was not an impossible dream. What happened next was more than anyone could have expected.



AN ORBITING GRAVITY OBSERVATORY called the Laser Interferometer Space Antenna (LISA) will detect passing ripples in space-time. LISA, a joint mission between NASA and the European Space Agency, consists of three satellites orbiting in a triangular configuration. The satellites can compare measurements with each other via laser beams. NASA

Changing course

In the wake of Pretorius' success, all of the researchers asked themselves the same question. "If Frans got it to work his way," Centrella explains, "then did we all need to change to Frans' method?" Some researchers decided to press ahead with their existing codes.

The RIT group members decided to focus efforts on their puncture method for treating moving black holes. It had been a major source of problems for them, but they came up with a solution.

Many in the field of numerical relativity believed that a puncture representing a black hole could not move. So researchers would just pin the puncture in the grid and let space-time move around it.

Campanelli and her colleagues decided to let the puncture move. To their surprise, the method produced spectacular results. Suddenly, Campanelli's group could track orbiting black holes all the way to merger.

The researchers presented the new success at the next numerical relativity meeting but met with disbelief. "People saw our simulations but didn't understand how you could move the black hole across the grid," Campanelli says.

It might have gone worse for Campanelli's group if Joan Centrella's team hadn't shown up with simulations that used the same method. "The community was just stunned silent," Centrella recalls.

The simulation of black hole mergers, from inspiral to ringdown, are now routine. "Now there are sessions at the American Astronomical Society meetings dedicated entirely to mergers," Centrella says. "And just a little while ago, we could not even get an orbit."

> "Frans was the classic lone gunman. He appeared at a conference and said 'Watch this.'"
> — Scott Hughes

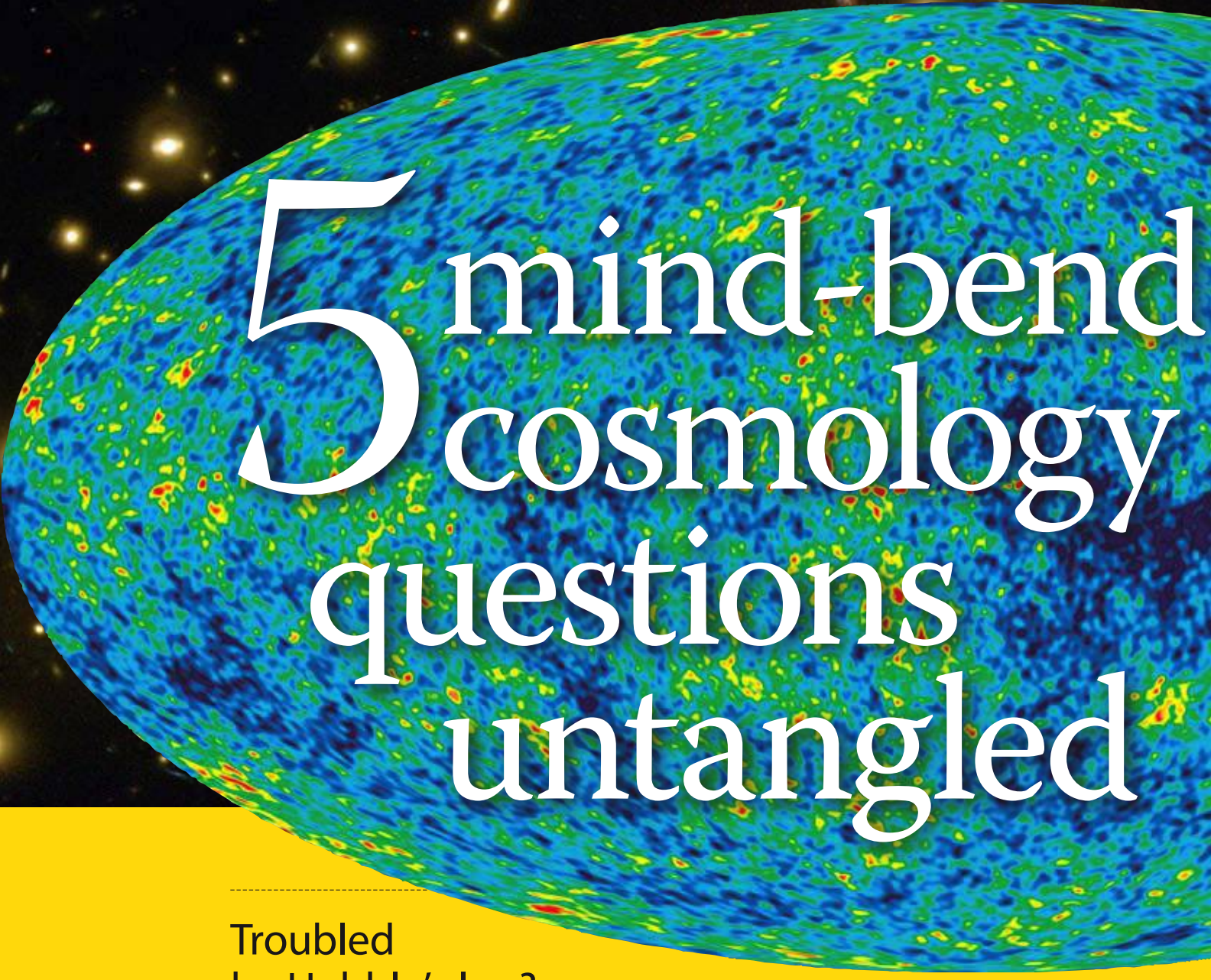
Black holes, bright future

Researchers are moving quickly to explore additional black hole merger scenarios, including mergers of black holes of different sizes and spins. "It's a feeding frenzy right now," Pretorius says. "And it will still take a few years until all the important cases have been mapped out."

Already, new surprises have appeared. Research with computer models shows that after a merger, the new, combined black hole experiences a powerful recoil force. In simulations, black holes blast away after mergers at speeds topping 625 miles (1,000 km) per second.

Simulated black hole mergers can now provide guidance to LIGO researchers and other gravity-wave observatories around the world. Sometime around 2013, LIGO will be upgraded to a more sensitive design, called Advanced LIGO. The improvements in sensitivity should finally give astronomers a telescope ready to detect black-hole mergers.

It has been a long, hard climb for LIGO scientists as they ready their detectors to identify passing gravitational waves. Numerical relativists experienced their own hard climb, and they are finally getting some satisfaction. They will be ready and waiting as LIGO turns its ear to the sky to detect the faint ripples of distant cataclysms.



5 mind-bend cosmology questions untangled

Troubled by Hubble's law? Perplexed by the Big Bang? Tune up your cosmic knowledge with these insights. /// BY LIZ KRUESI

Cosmology's goal — to understand the origin and evolution of the universe — is nothing if not ambitious. Less than a century ago, astronomers discovered that most galaxies are moving away from us and revealed the astounding fact that our universe is expanding. A few decades later, they realized a faint hiss of radio waves all over the sky arose from photons emitted shortly after the universe came into being. In 2006, a spacecraft called WMAP, which explores this cosmic microwave background, turned up compelling evidence that the universe underwent an early phase of hyper-expansion called inflation.

Some call today cosmology's golden age. Yet, for all its ongoing progress, some of cosmology's most fundamental ideas remain hard to grasp. *Astronomy* takes on the top five sources of cosmic confusion — the biggest stumbling blocks in understanding cosmologists' current portrait of the universe.

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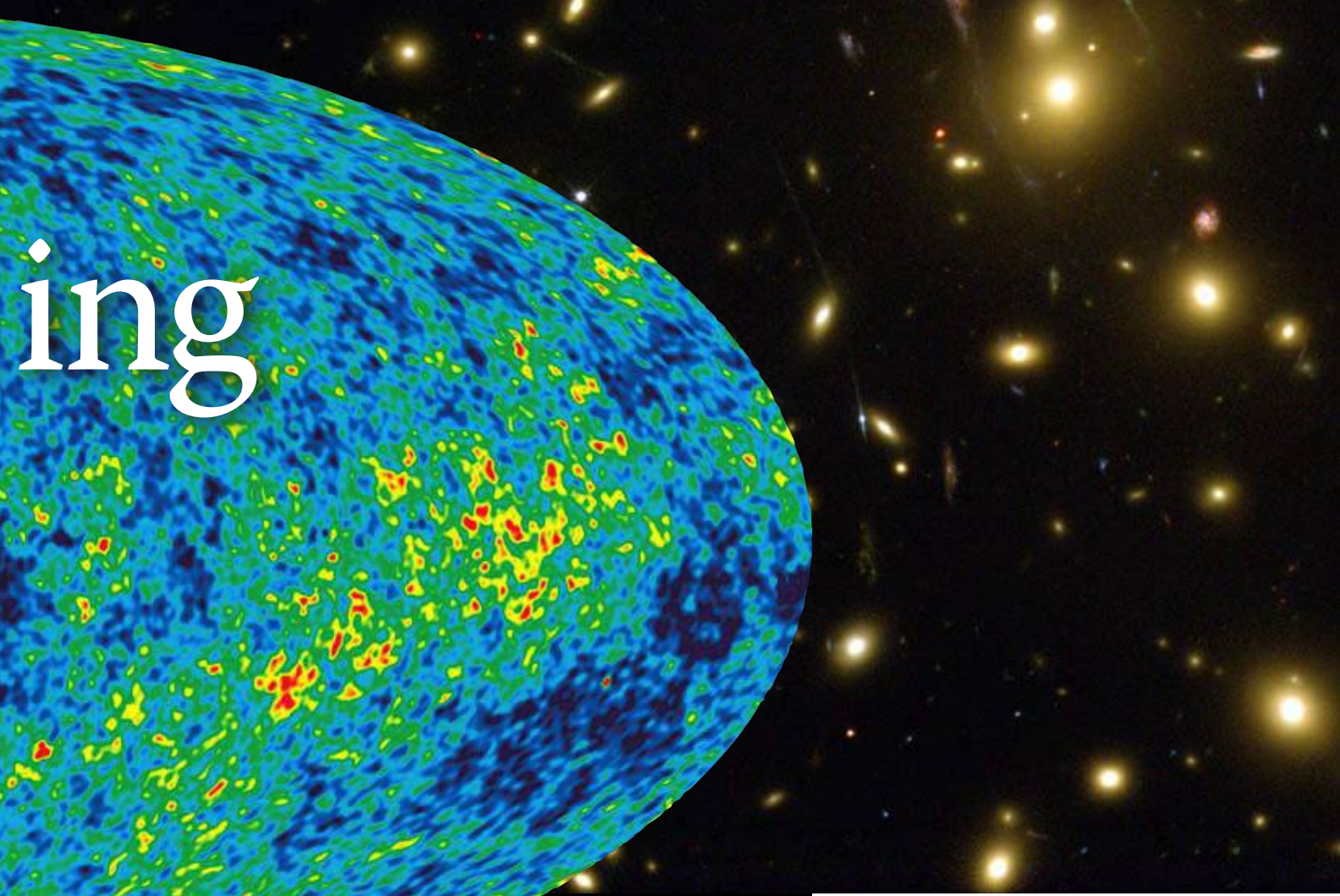


THE BIG BANG is a poor name for the event that gave rise to space, time, and all we observe — all we can observe, from the cosmic microwave background to the stars of our own galaxy. Nothing in the science of the Big Bang theory calls for the popular image of a gigantic cosmic explosion, say scientists. WMAP: NASA/WMAP SCIENCE TEAM; ABELL 2218 AND M100: NASA/ESA/STScI

1 If **distant galaxies** all are moving away from us, doesn't that mean we're at the **universe's center**?

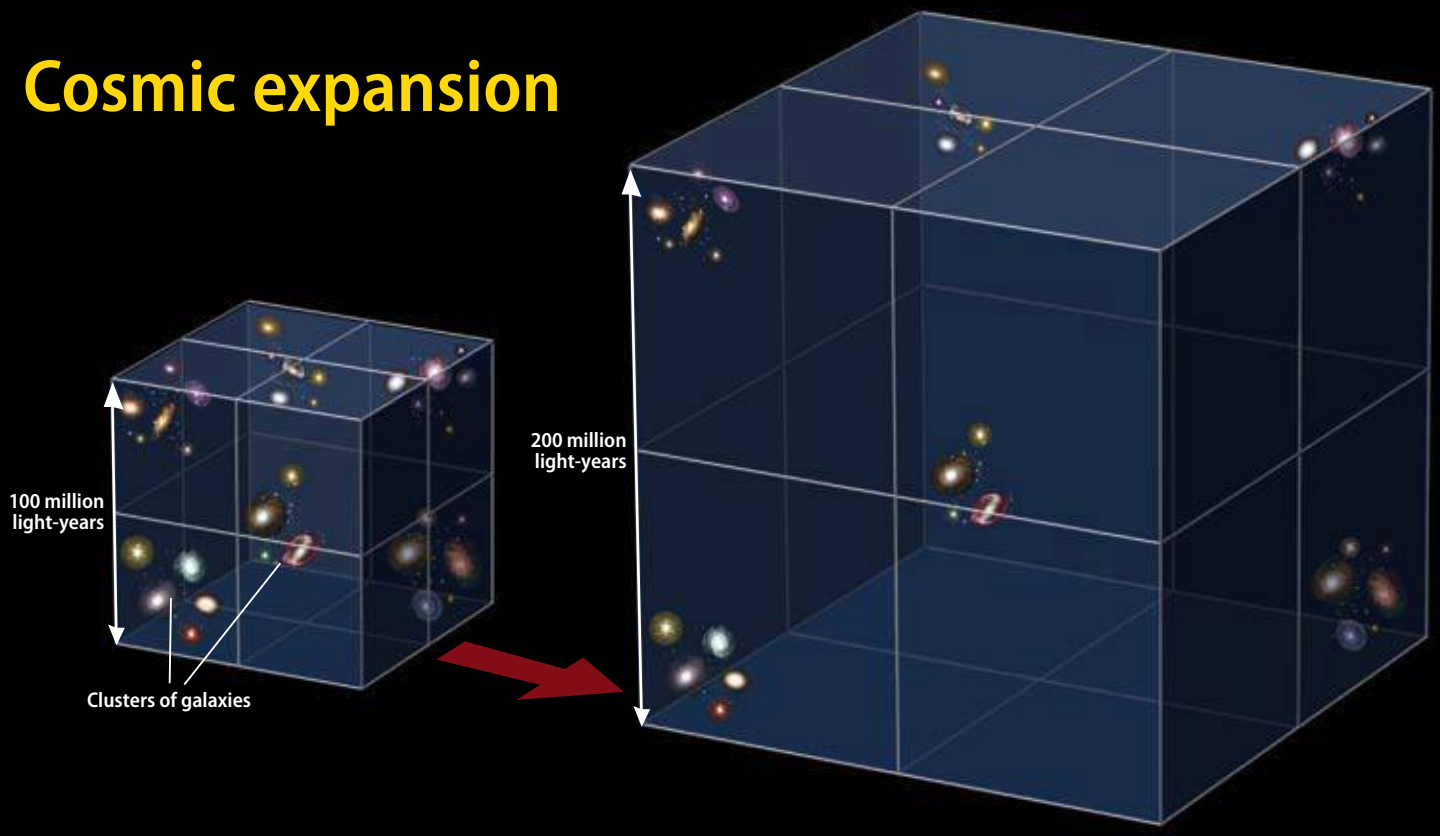
In a word, no.

In the 1920s, the work of Edwin Hubble and Milton Humason at California's Mount Wilson Observatory firmly established that all but the closest galaxies are moving away from us. Moreover, they saw a pattern — the more distant the galaxy, the faster it recedes. But this isn't motion through space. It's the systematic expansion of space itself, and it carries galaxies along for the ride.

In 1916, German theoretical physicist Albert Einstein published his general theory of relativity, which expanded on his earlier ideas by including how gravity affects the shape of space and the flow of time. A year later, Dutch astronomer

Liz Kruesi *is an associate editor of* Astronomy. *She enjoys discussing cosmological problems.*

Cosmic expansion



EDWIN HUBBLE'S DISCOVERY of the expanding universe is one of the most fundamental in the history of astronomy. It's also frequently misrepresented. In this illustration, six clusters of galaxies in a cube 100 million light-years across separate from one another as the cube doubles in size. There is no expansion center. From the perspective of an observer in any galaxy cluster, the other clusters all appear to be moving away. This creates the illusion that each observer lies at the center of the expansion. *ASTRONOMY:* ROEN KELLY

Willem de Sitter used Einstein's equations to show that a nearly empty universe must also be an expanding one. Hubble understood the pattern he saw in receding galaxies was exactly what one would expect in a universe made of "de Sitter space."

Light traveling through expanding space becomes stretched out. Individual photons lose energy, so a given spectral line appears shifted toward longer (redder) wavelengths. But signals — like the explosion of a supernova — become stretched, too.

Supernovae in distant galaxies last longer than they do in nearby galaxies — and the farther away they are, the longer they last. This means that space is stretching, and the galaxies embedded in the underlying fabric of space follow the fabric's movement away from other objects.

Astronomers often use a balloon as an aid for picturing the expanding universe. Stickers on the balloon's surface represent galaxies, and, as the balloon inflates to represent the expansion of space, the distance between each sticker grows. Unfortunately, most people try to push the analogy too far and ask what's in the balloon's center.

Here's a two-dimensional experiment that gets to the heart of the matter. Draw many dots on a piece of paper. Now, make an enlarged copy as a transparency. Place the copy on the original, and pick one dot — any dot — to be the viewpoint. "Regardless of where the dot is, 'observers' in each dot will see other dots moving away," explains Asantha Cooray of the University of California at Irvine. "This is exactly what happens in the universe with each galaxy moving away from each other."

Another way to imagine cosmic expansion is to picture a loaf of raisin bread. As the bread (space) expands, each raisin (a galaxy) sees the other raisins receding from it. The raisins themselves don't change — the underlying structure does. And each raisin has an identical point of view: All other raisins are moving away from it. John Mather, a cosmologist and 2006 Nobel laureate at NASA's Goddard Space Flight Center, says, "Picture a full space that expands with everything in it."

Cosmologists assume that over sufficiently large distances — and we're talking scales larger than clusters of galaxies — the universe looks the same to an observer located anywhere within it. This is an extension of relativity, which says there's no preferred frame of reference for physical interactions. Scientists call this assumption the cosmological principle, and they test it regularly. So far, it appears to be a good approximation of the universe's state.

2 What is the **expanding universe** expanding into?

This is another question that comes from stretching that balloon analogy of the expanding universe too far. The universe is self-contained. As difficult as it is to believe, the universe can expand without expanding into something else.

Einstein's relativity provided a new way of looking at the universe. It pictures gravity not as a force, but as curves in space-time. Matter and energy in a gravitational field move the way curved space-time dictates. Relativity's space-warping behavior predicts that gravity bends light.

In 1919, a total solar eclipse gave scientists direct evidence. If massive objects warp space, light from a distant star would be displaced if the star's light passed close to a large mass, like the Sun. The effect is small, but, sure enough, astronomers observed changes in the positions of stars near the Sun during the eclipse.

This is but one of many validations of Einstein's theory. Relativity gives modern cosmology a solid foundation. As de Sitter showed, space is a dynamic entity that can warp, shrink, and grow without the necessity of being embedded in some higher-dimensional space.

3 What kind of **explosion** was the **Big Bang**?

The Big Bang wasn't any kind of explosion.

"There is nothing in the physics — in the science — of the Big Bang that talks about an explosion," says Charles Bennett, lead researcher on the Wilkinson Microwave Anisotropy Probe (WMAP) project. WMAP has produced our most precise picture of the cosmic microwave background (CMB). These microwave photons have been traveling through space since electrons and protons first combined into atoms of neutral hydrogen some 380,000 years after the universe's birth.

Astronomers know the universe is slightly bigger, cooler, and less dense than it was yesterday — this is the nature of cosmic expansion. If we extrapolate backward, then, in earlier days, the universe must have been smaller, hotter, and denser than astronomers now observe it to be.

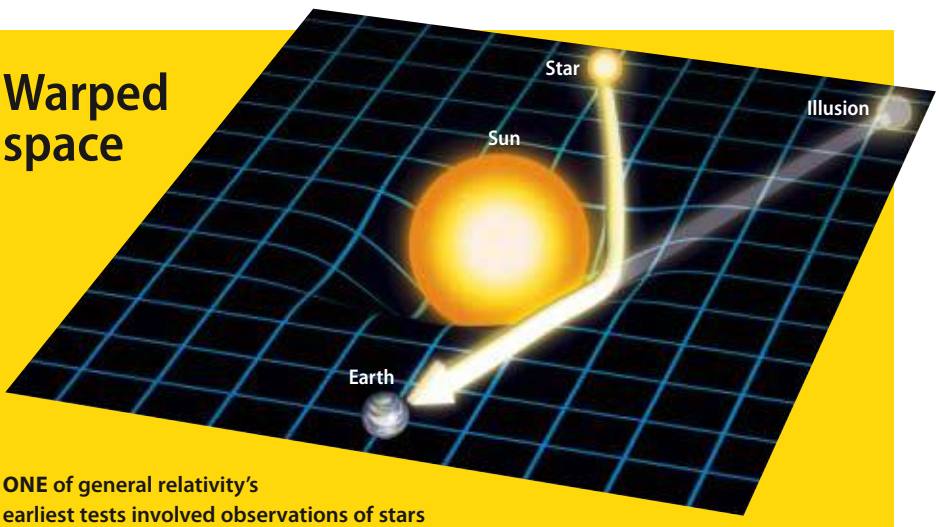
When the visible universe was half its present size, the density of matter was 8 times higher and the CMB was twice as hot. When the visible universe was 1/100 its present size, the CMB was 100 times hotter. When the visible universe was only one-hundred-millionth its present size, its temperature was 273 million kelvins above absolute zero. The density of cosmic matter was comparable to the air density at Earth's surface. These temperatures completely ionized the universe's gas into fast-moving protons and electrons.

"'Big Bang' is not an accurate name for the theory," Bennett explains. "What this theory describes is the expansion and the cooling of the universe. It doesn't describe an explosion at all."

But isn't the Big Bang an explosion in space? Its name implies a standard bang, such as a chemical explosion (like fireworks); once we have this image in our mind, it's hard to imagine the Big Bang as anything else. But the universe's beginning wasn't an explosion. It was closer to an unfolding, or creation, of matter, energy, time — and space itself.

"What would actually have been a much better name is the expanding-universe theory because it's really a theory of how the universe expands," says David Spergel, a WMAP team member at Princeton University in New Jersey.

Warped space



ONE of general relativity's earliest tests involved observations of stars during total solar eclipses. Starlight grazing the Sun, according to Einstein, bends as it follows space-time curved by the Sun's mass. Star positions measured near the eclipsed Sun appear slightly displaced from their actual positions. *ASTRONOMY*: ROEN KELLY

Hot stuff

The universe is expanding and cooling. It was smaller, hotter, and denser in the past — the basis of the Big Bang model.

13.7 billion years: The universe's age, give or take a few hundred million years.

93 billion light-years: The observable universe's present size.

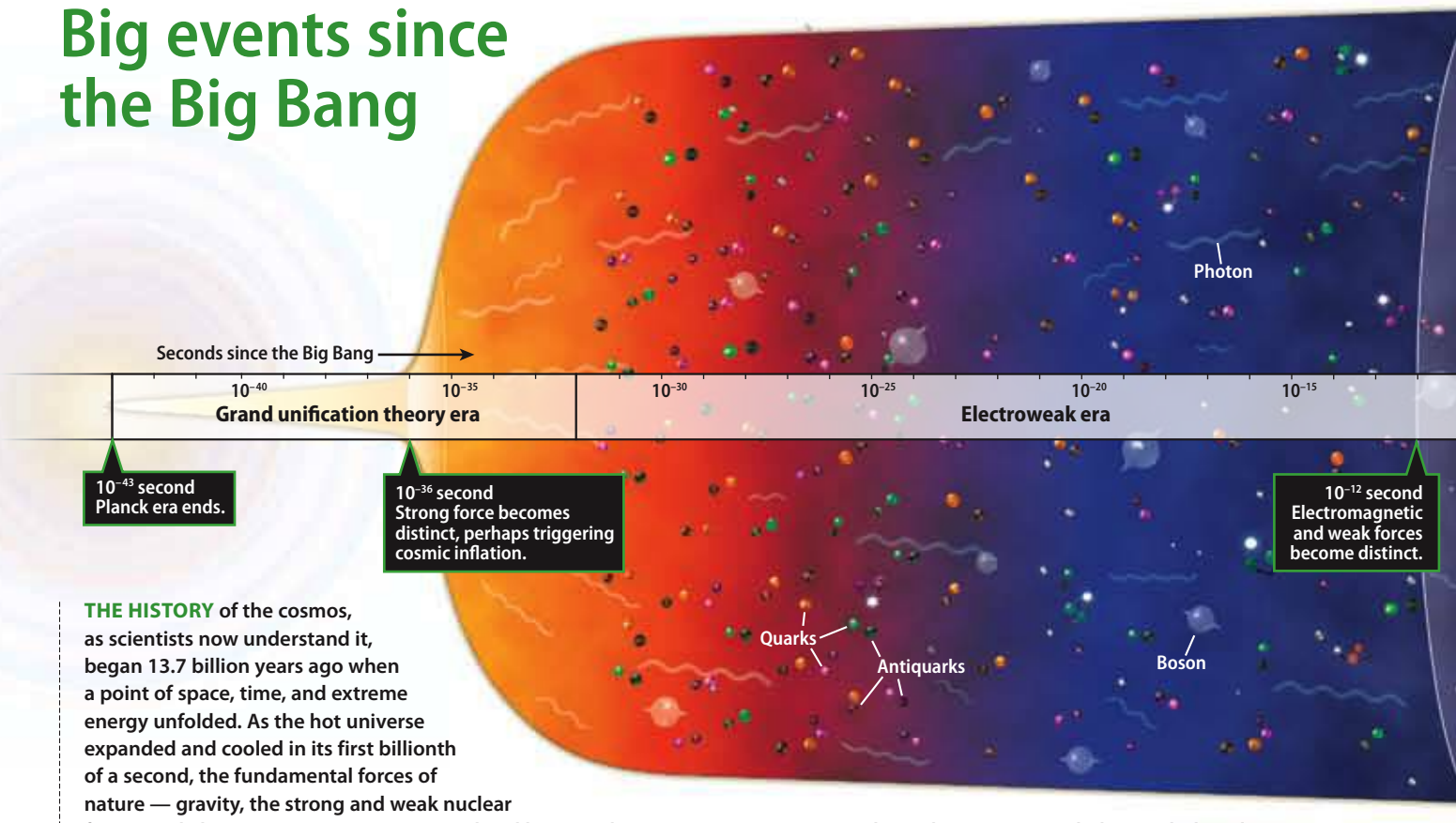
2.725 kelvins: The average temperature of the cosmic microwave background (CMB).

5% The proportion of ordinary matter — humans, planets, stars — the universe contains.

23% The share of dark matter in the universe. This is an unidentified substance that interacts gravitationally with ordinary matter, but not with the other three fundamental forces (electromagnetism and the weak and strong nuclear forces).

72% The portion of dark energy in the universe. Dark energy is an unidentified force that accelerates cosmic expansion.

Big events since the Big Bang



THE HISTORY of the cosmos, as scientists now understand it, began 13.7 billion years ago when a point of space, time, and extreme energy unfolded. As the hot universe expanded and cooled in its first billionth of a second, the fundamental forces of nature — gravity, the strong and weak nuclear forces, and electromagnetism — separated and became distinct. Next, subatomic particles appeared and, over the next 3 minutes, protons fused to make helium and a few other nuclei. About 380,000 years later, the universe cooled enough that electrons could bind with nuclei and make the first atoms. Photons flew free to make the cosmic microwave background (CMB). *ASTRONOMY:* ROEN KELLY

4 What came **before** the **Big Bang**?

No one knows. Maybe nothing existed before our universe or, says Harvard University's Avi Loeb, perhaps the universe "goes through cycles of Big Bangs. But there is no data to support one or the other hypothesis." Using the known laws of physics, cosmologists can extrapolate back to a fraction of a second (10^{-43}) after the Big Bang to the so-called Planck era, but there they must stop. Science simply cannot yet answer this question.

Scientists are stuck with two separate theories. One, quantum mechanics, explains the world of the very small, while the other, general relativity, explains the large-scale universe. Both work in their own regimes, but they are incompatible with each other. Says Loeb: "We need a theory that unifies quantum mechanics and gravity in order to extrapolate all the way back to the Big Bang."

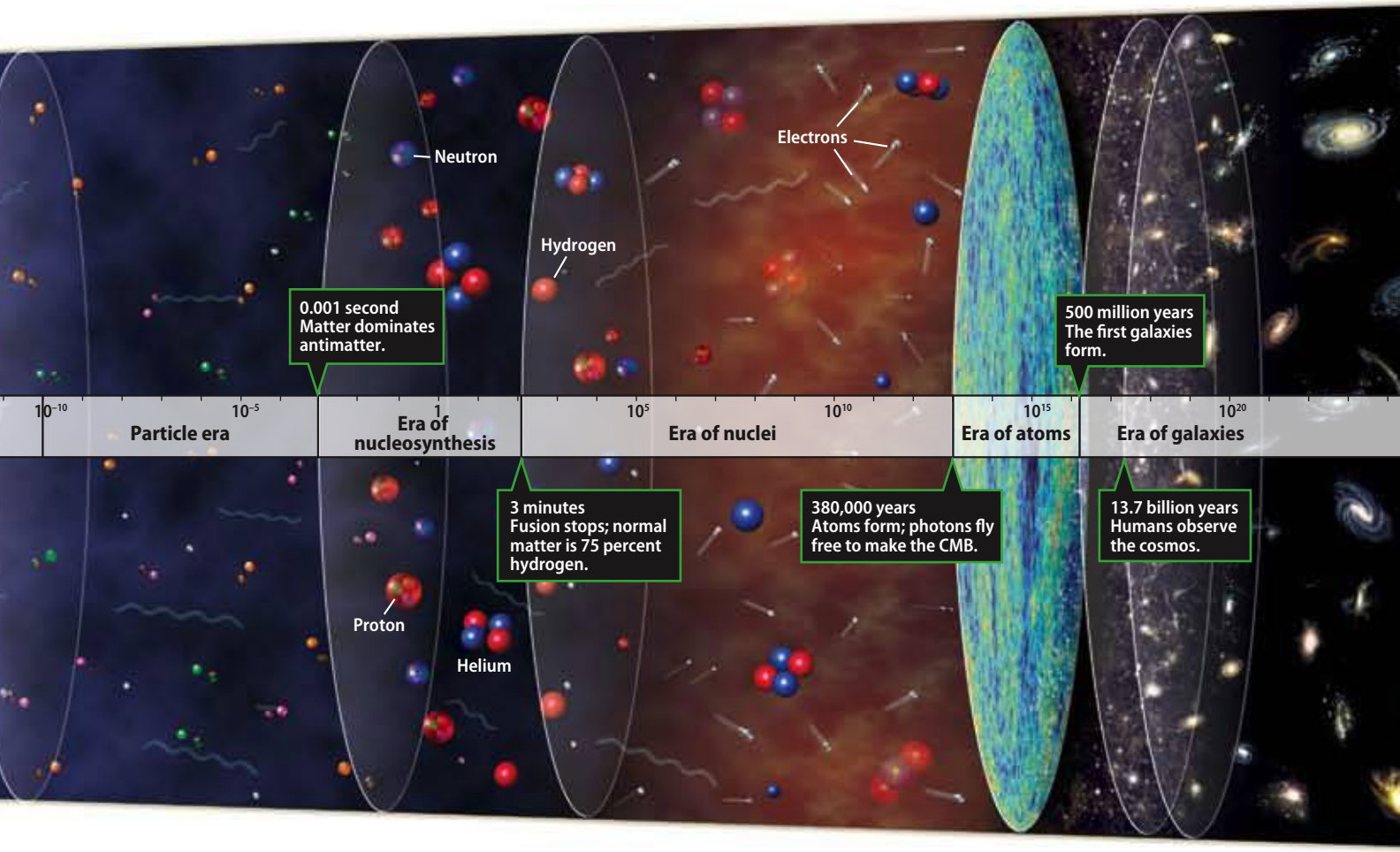
After centuries of research, physicists know there are four fundamental physical forces: gravity, electromagnetism, and the strong and weak nuclear forces. Theorists have unified electromagnetism and the weak force. When the universe was only 1 trillionth of a second old, it became cool enough that this "electroweak" force separated into the two forces we now see.

Attempts to unify the strong and electroweak forces haven't yet met with success, but scientists believe that, even earlier in cosmic history, all of the fundamental forces were one. But gravity — so far, the domain of relativity — remains problematic.

Superstring theory attempts to unite relativity and quantum mechanics. In this view, all elementary particles are vibrating loops of energy called strings. Each type of string — whether it corresponds to an electron or a top quark — vibrates at a particular frequency.

Superstring theory has a testable consequence called supersymmetry, which posits the existence of unseen superpartners for every type of elementary particle known. The Large Hadron Collider (LHC) at the European Organization of Nuclear Research in Geneva, scheduled to restart

A MASSIVE EXPERIMENT section nears the end of a 10-hour descent into the Large Hadron Collider's cavern December 12, 2006. Physicists hope this and other detectors will provide evidence for supersymmetry. MAXIMILIEN BRICE/CERN



operations late in 2009, is expected to reach energies where it could prove or disprove supersymmetry.

5 What's **outside** the universe?

For all we know, the universe is infinite.

WMAP data verify earlier ideas that the universe experienced a hyperfast growth spurt cosmologists call inflation. So, it's likely the universe is much bigger than what we now observe.

It's useful to distinguish between the universe itself — everything that arose from the Big Bang — and the "observable universe" — everything we can detect. The latter quantity constantly changes as astronomers make new obervations.

Cosmologists know the universe's age from observations of the cosmic microwave background: 13.7 billion years. And because light travels at a finite speed, observers on Earth can observe only light that has managed to reach us. Because we can see 13.7 billion light-years in any direction, the observable universe must be twice that size, right?

Wrong. The stuff we now see in the CMB emitted its light 13.7 billion years ago, but, since then, it condensed into galaxies, and, thanks to the expanding universe, those galaxies are now about 46.5 billion light-years away. So, astronomers peg the size of the observable universe at about 93 billion light-years across.

Everyone knows Einstein's theory of relativity says light's speed is the ultimate speed limit for objects in space. But this doesn't apply to the expansion of space itself. The universal speed limit has a few exceptions in extreme cases — the universe's expansion is one of them.

The observable universe has an edge — scientists call it our horizon — bounded by the speed that light travels. What's on the other side? "As time goes on and the universe expands, more of the universe enters our horizon," explains Adam Riess of the Space Telescope Science Institute in Baltimore. Cosmologists say the universe beyond that which we can detect is "more of the same," he says.

Physical cosmology, a branch of science less than a century old, has brought forth some of its greatest successes in the past few years. They include pinning down the age of the cosmos and discovering that the universe is not only expanding, but its expansion is somehow accelerating. Yet cosmologists make no claim that our current model of the universe is complete. Saul Perlmutter of the Lawrence Berkeley Laboratory calls the Big Bang model "a working hypothesis … an amazingly successful first draft."

This is good — many astronomers would find the universe a bit disappointing if we answered some of the biggest questions after such a short investigation. New detectors and experiments — both Earth-based, such as the Large Hadron Collider, and space-based, like WMAP's successor, Planck — will let scientists put what we think we know about the universe to the test. Is supersymmetry — and, by extension, superstring theory — for real? What fuels cosmic acceleration?

If the past is prologue, we should expect the unexpected.

What if string theory is

If it is, then dark matter, dark energy, and cosmic inflation are in big trouble. /// BY STEN ODENWALD

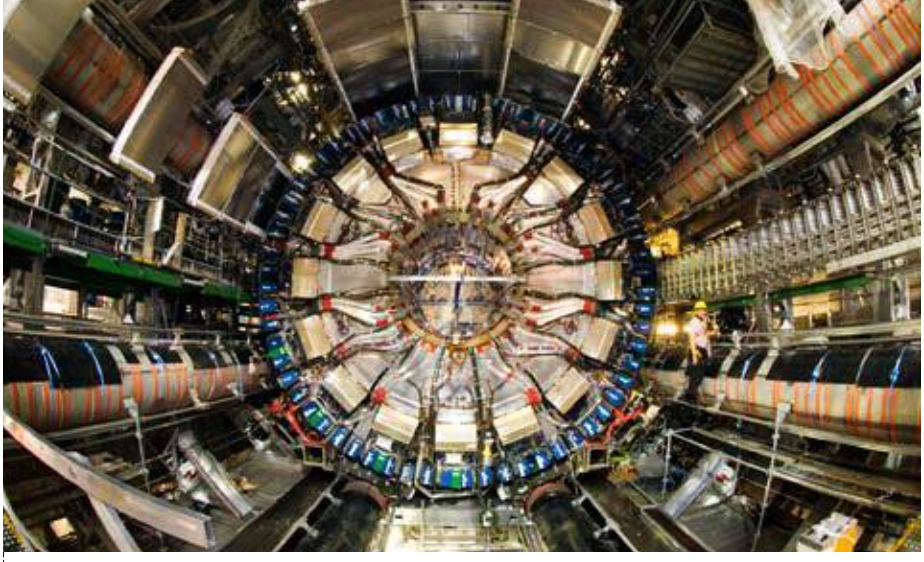
Scientists pin their hopes of unifying nature's fundamental forces to a single concept crafted over the course of 3 decades by thousands of mathematicians and physicists. It's called superstring theory.

Its basic ingredients are one-dimensional strings of pure energy that exist in a 10-dimensional universe, four of which are our familiar spatial dimensions plus time. Strings' vibration and movement create the fabric of space itself, along with all of nature's fundamental forces and elementary particles.

Now, imagine a future in which physicists are delivered the bad news: irrefutable data proving superstring theory doesn't work in our physical world. We're nowhere near such a crisis today, but it's sobering to realize what we stand to lose if physics' best bet proves to be a complete dead end.

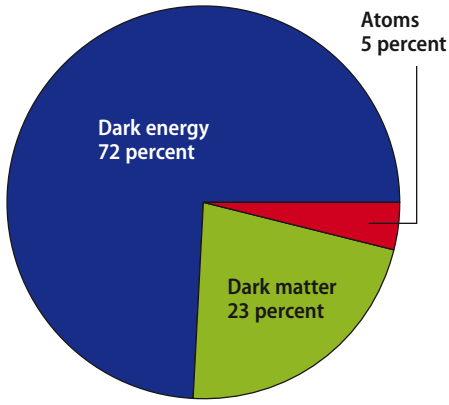
WRONG?

IF CURRENT THEORIES about supersymmetry are correct, every elementary particle has a massive superpartner not yet detected. Scientists hope to detect some of these particles using the Large Hadron Collider, which smashes atomic nuclei to liberate the fundamental constituents of matter. DON DIXON FOR *ASTRONOMY*



SCIENTISTS AT CERN will use the Large Hadron Collider's ATLAS detector to smash together high-velocity proton beams. The resulting subatomic debris should reveal fundamental particle processes. The ATLAS experiment is one of the largest collaborative efforts ever attempted in the physical sciences. The project involves 2,500 physicists from 169 institutions in 37 countries. CERN/CLAUDIA MARCELLONI

Cosmic constituents



COSMOLOGISTS' best tally of cosmic content comes from NASA's Wilkinson Microwave Anisotropy Probe (WMAP). Normal matter accounts for only about 5 percent of the total. *ASTRONOMY*: ROEN KELLY

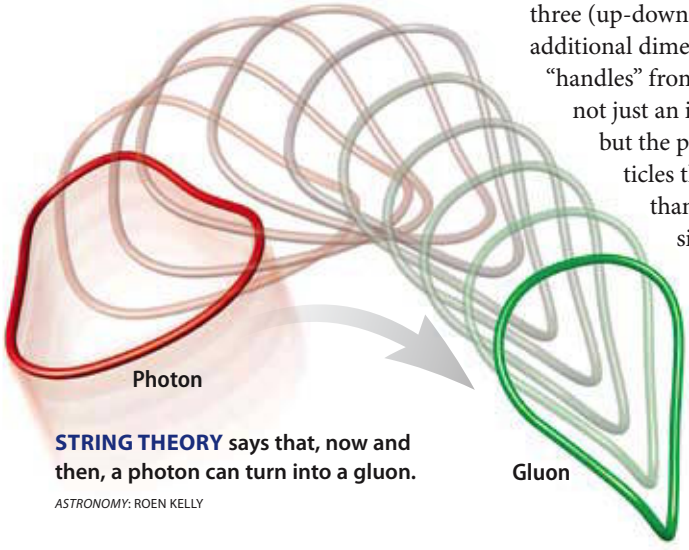
Extra dimensions

Superstring theory is based on three key ideas that remain experimentally unproven after 30 years of research: the principle of supersymmetry, additional spatial dimensions, and gravity as a force defined by the exchange of quantum particles.

Supersymmetry is a mathematical principle that allows force-carrying particles, such as photons and gluons, to transform into one another. It also allows the unification of gravity with other forces because its particle, which some call the graviton, can transform into one of the other force-carriers. Although this idea is mathematically elegant, and puts gravity on an equal footing with the other forces, no one has ever detected, for example, a photon turning into a gluon. Luckily, other ways to search for supersymmetry exist.

If nature follows supersymmetry, then every normal particle has a superpartner: Electrons partner with "selectrons," photons with "photinos," quarks with "squarks," and so on. These superpartners haven't been seen yet, but scientists built a new accelerator, the Large Hadron Collider (LHC), at the European Organization for Nuclear Research (CERN) in Switzerland to find them. Researchers hope experiments with the LHC will turn up at least a few of the lightest superparticles. Such a success would be a prelude to confirming the most bizarre physics idea of the last 80 years — extra dimensions to space.

Identity change



STRING THEORY says that, now and then, a photon can turn into a gluon. *ASTRONOMY*: ROEN KELLY

Space-time is just the start

Conventional superstring theory requires extra dimensions to space beyond the usual three (up-down, left-right, near-far). These additional dimensions give physicists extra "handles" from which they can fashion not just an improved theory of gravity but the properties of the known particles themselves. Vastly smaller than a proton, the extra dimensions appear as six additional coordinates attached to each point in space.

They actually form their own closed, six-dimensional spaces that must be everywhere. Otherwise, particles would take on different properties as they move through our three-dimensional world. There are trillions of possible six-dimensional geometries, each calling into existence a unique universe with specific physical laws, particles, and forces. Which one is ours?

Some researchers feel all geometric possibilities exist in the multiverse — the collection of all possible universes with all possible physical laws logically allowed by superstring theory. Ours, then, is a Goldilocks Universe, where exactly the right six-dimensional geometry allows the existence of life as we know it. There may be 10^{100} universes that fail this challenge. There may be others in which new, unthinkable possibilities for life could flourish.

If extra dimensions really exist, they'll change the behavior of gravity at small distances. In 2003, John Price of the University of Colorado at Boulder and his colleagues announced an ultra-precise measurement of gravity at scales of one-tenth of a millimeter. The team saw no departure from gravity's inverse-square law, in which the force of attraction decreases by the square of the distance between bodies. So, the hunt resumes below this limit to test other extra-dimensional possibilities.

"We have a number of hints from experiments and theoretical ideas that make us think they're probably out there," says Joseph Lykken, a physicist at Fermi

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Astronomer **Sten Odenwald** *works at NASA's Goddard Space Flight Center in Maryland and is investigating the cosmic infrared background.*

National Accelerator Laboratory in Batavia, Illinois. "That's why we're so excited about looking for them."

If scientists validate superstring theory, we'll see the birth of the first unified description of the physical world. Along the way, we'll have to make peace with the idea of a multiverse in which trillions of other universes may exist, each with its own natural laws, forces, and particles.

But what would happen if all these ideas are wrong? String theory would go down in history as the most spectacular wrong turn science has ever taken. It will have sent thousands of physicists on a spectacular wild-goose chase, while simultaneously revolutionizing obscure subjects in pure mathematics.

Forget supersymmetry?

If extra dimensions don't exist, then supersymmetry doesn't either. Without both of these cornerstones of string theory, physicists would be left with what they refer to as the standard model.

The standard model combines electroweak theory (EW) — itself a combination of electromagnetism and the weak nuclear force — with a separate theory of the strong nuclear force called quantum chromodynamics (QCD). Each part behaves like a train on a separate track. But just as electricity and magnetism were unified into electromagnetism, the standard model's EW and QCD are so similar that they, too, must be unified.

Grand unification theories (GUTs) tried to do just this. Physicists worked with dozens of prospects between 1975 and 1980; most failed. Many predicted the proton, the foundation of atomic nuclei, would rapidly decay; some introduced faster-than-light tachyons as new physical particles.

None turned out to work very well once physicists puzzled out their intricate mathematics and compared them to the real world. Physicist Mark Srednicki at the University of California, Santa Barbara, once complained about one candidate, "It is impossible to get this pile of junk to come out anything like the standard model."

In some respects, a world without superstring theory isn't so bad. The standard model and ordinary general relativity hold that all astronomers need to describe accurately most of the phenomena they study, from galaxy evolution and supernova detonations to the extreme physics of neutron stars and black holes.

As for unification, the late physicist Richard Feynman once said, "Perhaps it is difficult for physicists to unify gravity with the other forces because nature never intended for them to be unified in the first place."

Cosmic trouble

Astronomers have also discovered there is far more to the universe than what we can see. The standard model has absolutely no place in it for dark matter and dark energy, ingredients that constitute 95 percent of the universe's gravitating "stuff."

And it gets worse. Without supersymmetry, some physicists have proven that the energy of empty space would be so enormous that the universe would instantly collapse.

Only by understanding physics beyond the standard model can we hope to understand how the vacuum and the universe's dark side work. And only string theory appears able to serve as a reliable mathematical guide to that larger universe.

Another major disaster to astronomy would be in our understanding of the largest structures in the universe and the universe's large-scale smoothness revealed by studies of the cosmic microwave background (CMB).

Inflation, a super-fast expansion of the universe when it was less than a trillionth of a trillionth of a second old, explains observations of the CMB made by satellites such as NASA's Wilkinson Microwave Anisotropy Probe (WMAP). But it can't account for

LITERALLY trillions of possible six-dimensional geometries exist, each calling into existence a unique universe. Which one is ours?

STRING SPEAK

GENERAL RELATIVITY
Albert Einstein's formulation of gravity, which shows that space and time communicate the gravitational force through their curvature.

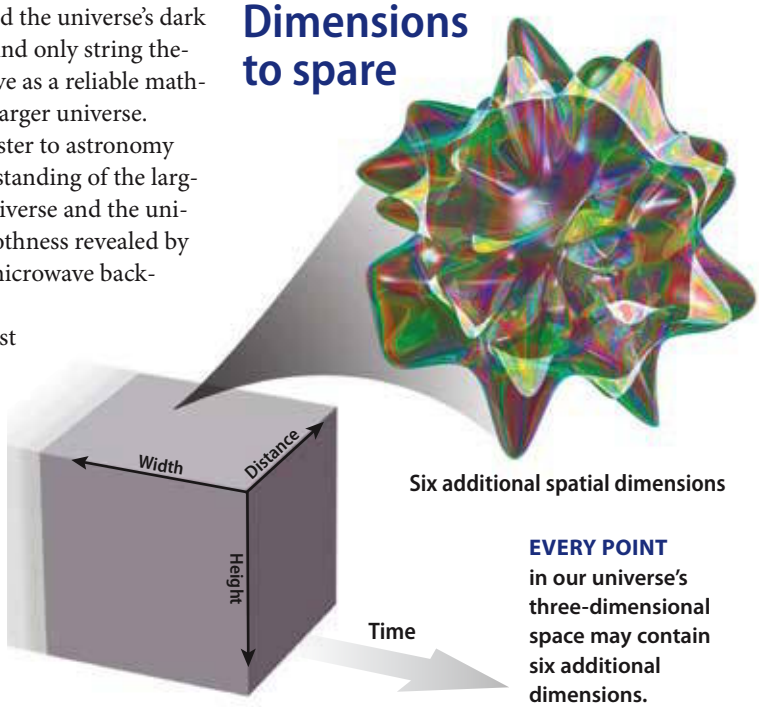
GLUON
The smallest bundle of the strong nuclear force, which holds atomic nuclei together.

QUANTUM MECHANICS
Laws governing the universe on subatomic scales in which uncertainty and the dual nature of waves and particles become apparent.

STANDARD MODEL
A theory of interactions of nature's most fundamental known particles (e.g., electrons and quarks) developed in the late 1960s and early 1970s. Its inability to explain gravity suggests a more fundamental theory exists.

STRING THEORY
A unified theory of the universe postulating that the fundamental ingredients of nature are not particles but one-dimensional filaments called strings. String theory unites quantum mechanics and general relativity, which are otherwise incompatible; often short for superstring theory.

Dimensions to spare



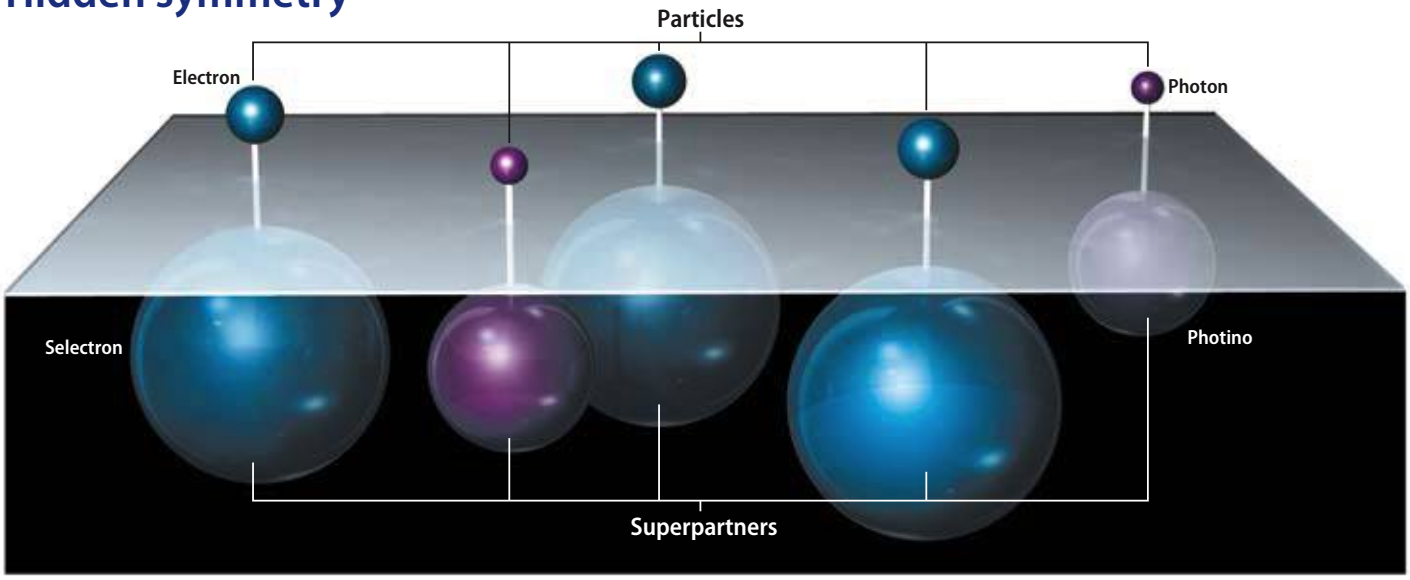
Six additional spatial dimensions

Three spatial dimensions

EVERY POINT in our universe's three-dimensional space may contain six additional dimensions.

ASTRONOMY: ROEN KELLY

Hidden symmetry

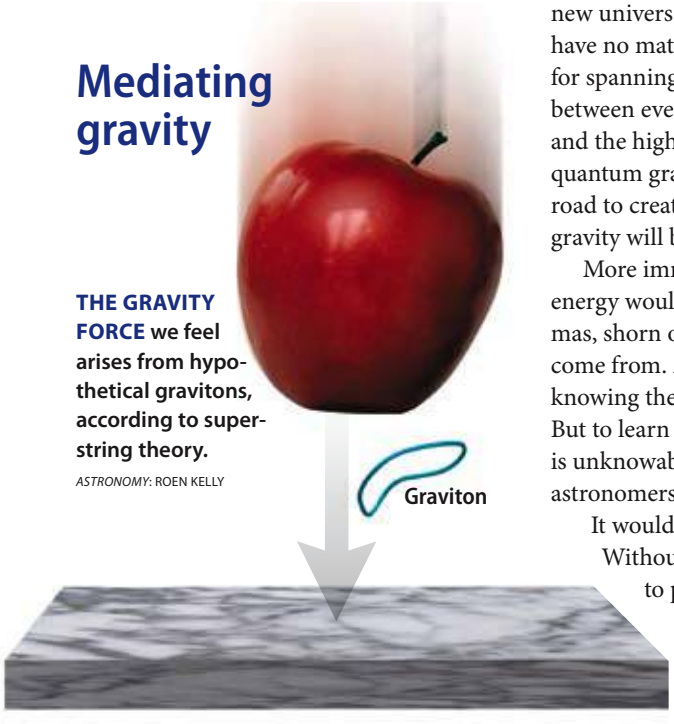


SUPERSYMMETRY envisions a "shadow world" that links known particles to massive superpartners not yet detected. *ASTRONOMY:* ROEN KELLY

the small-scale structure that led to galaxy formation. Only by reaching back to the era before inflation, often called the quantum-gravity era or Planck Era, can cosmologists explain why today's universe looks the way it does at galactic scales.

The standard model and ordinary general relativity aren't enough. Only some larger, more encompassing theory can lead the way. "It is hard to find a serious paper about particle phenomenology that doesn't in some way use the tools of superstring theory," says Stanford University physicist Leonard Susskind. "Furthermore, we all agree that the origin of elementary particles is most likely at the Planck scale and cannot be understood without a good theory of quantum gravity."

Mediating gravity



THE GRAVITY FORCE we feel arises from hypothetical gravitons, according to superstring theory. *ASTRONOMY:* ROEN KELLY

In the 1980s, when Alan Guth at the Massachusetts Institute of Technology and Andrei Linde, now at Stanford University, first developed the inflation idea, it had nothing to do with string theory, extra dimensions, or supersymmetry. Refinements to inflation have come only by borrowing ideas from string theory.

End game

Without superstring theory, we'd lose the intriguing philosophical prospects for the multiverse, with its infinite and eternal creativity in spawning new universes. We'd have no mathematics for spanning the gap between everyday physics and the high energies where quantum gravity operates. The road to creating a quantum description of gravity will be a murky one.

More immediately, dark matter and dark energy would remain imponderable enigmas, shorn of any clues about where they come from. Astronomers can live without knowing the quantum properties of gravity. But to learn that 95 percent of the cosmos is unknowable would be a bitter pill for astronomers to swallow.

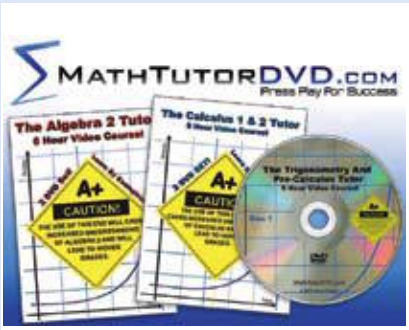
It would be even worse for physicists. Without a logical framework in which to pose and answer questions, our inquiries into the fundamental aspects of the physical world would devolve into semantic quibbles. Other impacts prevent us from simply turning back the theoretical clock to the 1970s.

TO LEARN THAT 95 percent of the cosmos is unknowable would be a bitter pill for astronomers to swallow.

"We would be ignoring the vast amount of mathematical knowledge that has been gained over the subsequent years, mostly from string theory," Susskind explains. "That is just not going to happen. The changes in our theoretical understanding of quantum field theory, gravity, and black holes are completely irreversible. The mathematics of superstring theory has even worked its way into nuclear physics and heavy ion collisions, as well as into condensed matter physics."

Historically, there are many examples of scientists forced to abandon ideas. Steady-state cosmology lasted nearly 30 years before science tossed it aside. While string theory is sparse on experimental validation, the situation is not so different from general relativity in its early days, when difficult mathematics made calculating a prediction extremely challenging.

Princeton University physicist Ed Witten once described string theory as 21st-century physics glimpsed long before its time. Let's hope it doesn't represent a bit of 25th-century mathematics, too.



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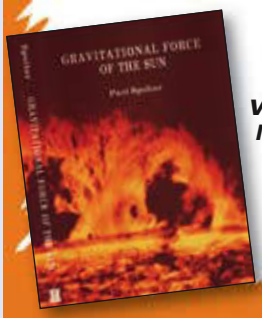

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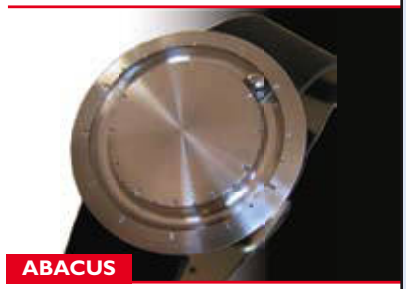

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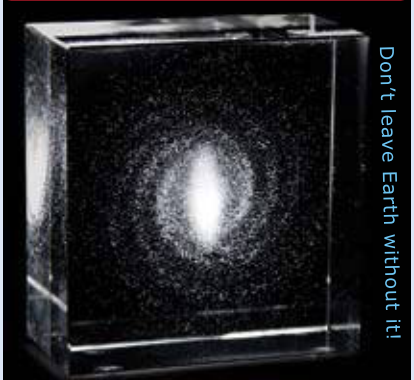

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THE ANTENNAE (NGC 4038/9) are a pair of merging galaxies in the constellation Corvus. The collision triggered a burst of star formation. Stellar nurseries show up as reddish clouds of hydrogen gas, while young star clusters appear as bright blue blobs. NASA/ESA/HUBBLE HERITAGE TEAM (STScI/AURA)